TREE-BIOMASS DECOMPOSITION, NITROGEN DYNAMICS, AND MAIZE GROWTH UNDER AGROFORESTRY CONDITIONS IN THE SUBHUMID HIGHLANDS OF KENYA

By

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By

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Declining crop yields, consequent to continuous cropping without external addition of adequate nutrients, is a major problem facing smallholder farmers in the tropics. The high cost of inorganic fertilizers has led to increased interest in the use of leafy biomass from woody species as a source of nutrients to annual crops. This dissertation reports the results of a study, conducted in the subhumid highlands of Kenya since 1992, on the influence of soil-incorporated leaf prunings of two agroforestry tree species (Calliandra calothyrsus--calliandra and *Leucaena leucocephala*--leucaena) on maize yield and soil fertility status in sole cropping and alley cropping systems.

Inclusion of calliandra hedges on cropland (alley-cropping) adversely affected crop yields during the four-year study period, whereas alley cropping with leucaena

increased crop yields. In all the treatments, mineralization of soil N was at its peak four weeks after maize planting. Cumulative mineralized N at week 20 ranged from 115 to 360 kg N/ha/season; the non-alley-cropped, nonfertilized control giving the lowest, and the prunings-incorporated treatments giving the highest amounts of N. Total N uptake by maize, ranging from 40 to 160 kg/ha/season, was lowest in the alley-cropped, prunings-removed plots, and the highest in the prunings-incorporated plots. Studies with ^{15}N indicated that soil application of N-rich biomass contributed more to the long-term build up of soil N than to meeting the nutrient requirements of the current season's crop: the largest fraction of N (55% to 69%) in the tree biomass that was added to the soil was left in the soil N pool at the end of the current cropping season, 8% to 13% was recovered in the maize, and 2% to 3% in the tree hedges; 20% to 30% could not be accounted for.

A separate study on decomposition of tree-leaf biomass of some commonly used agroforestry tree species in the region revealed that the prevailing general assumption that decomposition of tree biomass is determined predominantly by plant quality factors was not always true: during seasons of erratic climatic changes (e.g., fluctuating temperatures), climatic factors were more important than plant quality factors in influencing the rate of biomass decomposition.

CHAPTER 1
GENERAL INTRODUCTION

Production of adequate food to meet the needs of an increasing population is a major challenge for most developing countries and in particular those of tropical Africa (Brown et al. 1995). In the past, smallholder farmers practicing shifting cultivation in these regions relied on long fallow periods to regenerate the fertility of the land exhausted during the cropping period (Nye and Greenland 1960). However, it is no longer possible to maintain the long fallow periods in many areas of the tropics due to the high increase in population (FAO 1989; Drechsel et al. 1996). In some areas, shifting cultivation has been abandoned altogether and farmers are cropping their lands continuously with additions of no or minimal nutrients to the soil. This has led to declined crop yields and reduced per capita food production (Brown et al. 1995).

Though farmers are aware of the declining soil fertility (expressed by declining crop yields), in most cases they do not have readily available resources to replenish soil fertility. Chemical (inorganic) fertilizers could be used to maintain soil fertility and increase crop yields, however, they are not widely used because they are

unaffordable by most smallholder farmers (FAO 1990; Vlek 1990). Application of cattle manure to the soil is a widely used means of maintaining soil fertility and crop productivity. However, the quantity of manure produced and applied is often too low to sustain continuous crop production at meaningful yield levels (Ikombo 1984; Batiano and Mokwunye 1991).

There is therefore an urgent need to develop appropriate technologies for soil fertility enhancement to allow the land to produce more food to meet the ever rising food demand. These should be low input, economically, and environmentally sound soil management technologies that are acceptable to smallholder farmers. Agroforestry technologies have been proposed as some of the viable approaches. Some such technologies that have given promising results include alley cropping (hedgerow intercropping), biomass transfer (cut-and-carry) systems, improved fallows, parkland systems, and shaded perennial systems. Leafy biomass used in these technologies are able to increase crop yields mainly due to their N contribution to the soil.

The overall objectives of the research presented in this dissertation were to evaluate the influence of soil-incorporated leaf biomass of agroforestry trees on soil fertility and maize yield, and to gain more understanding on the processes involved in the fate of N released from the decomposing biomass. The specific objectives were to

1. evaluate the influence of soil-incorporated leaf biomass on maize yields and soil properties in sole- and alley-cropped maize systems,

2. investigate the rate of mineralization of soil-incorporated biomass and the extent of synchrony between mineralized N and its uptake by crop,

3. trace the path of N in ^{15}N-labeled biomass when soil-incorporated in an alley cropping situation, and

4. prepare a predictive model of decomposition patterns of tree biomass trees in the highlands of Kenya.

The study is presented in seven chapters. Following this introductory chapter (Chapter 1) is a review of the current literature (Chapter 2). The four chapters that follow (Chapters 3 to 6) cover specific aspects of the studies: Chapter 3 discusses soil fertility changes and maize yield with calliandra and leucaena; Chapter 4 describes soil N mineralization, uptake, and recovery by maize; and Chapter 5 reports the extent of ^{15}N release from labeled prunings and its recovery by maize crop and hedgerow tree species. Chapter 6 describes decomposition patterns of tree biomass across different microregions in the tropical highlands of Kenya. Finally, Chapter 7 provides a synthesis and general recommendations.

CHAPTER 2
LITERATURE REVIEW

Introduction

One of the conceptual foundations upon which tropical agroforestry research was initiated two decades ago is that trees help maintain soil fertility and support the growth of associated crops (Nair 1984). Various hypotheses emanating from this concept have been tested in a large number of situations (Young 1989; 1997), and such efforts have formed an important part of scientific research in tropical agroforestry (Sanchez 1995; Nair 1997). Today, a substantial body of knowledge is available on the role of trees in the maintenance of soil fertility in agroforestry systems (Rao et al. 1997). The objective of this chapter is to briefly review the current state of knowledge on the role trees play in the maintenance of soil fertility in tropical agroforestry systems that are relevant to this study. These include alley cropping, improved fallows, and parkland systems. The shaded perennial system, another major tropical agroforestry system (Beer et al. 1997), is not reviewed here because it is not directly relevant to this study. These technologies have shown promising results in improving soil fertility and crop production. Processes like biological

dinitrogen fixation (BNF) by trees, decomposition and mineralization of tree biomass, and nutrient uptake by trees from deeper soil layers that contribute toward soil fertility maintenance in agroforestry systems will also be reviewed.

Alley Cropping

Alley cropping (also referred to as hedgerow intercropping), developed by scientists at the International Institute for Tropical Agriculture (IITA) in the early 1980s, is one of the most studied agroforestry technologies. It consists of growing food crops in the alleys formed by hedgerows of multipurpose trees and shrubs (MPTs) that are usually N_2-fixing. The hedgerows are cut back (lopped) and periodically pruned during the cropping season to prevent shading of the companion crops. The prunings provide nutrients when incorporated into the soil as green manure or spread on the soil surface as mulch (Kang et al. 1990). By retaining woody perennials in crop production fields on a continuing basis, alley cropping simulates the role of fallow in soil fertility regeneration in shifting cultivation (Nair 1993).

Though alley cropping technology has generated a lot of data to date, it seems that the system performance is location-specific and greatly influenced by the choice of tree species and the type of management adopted.

Generalizations and extrapolation of results to seemingly similar environments is, therefore, difficult and as well as misleading (Nair et al. 1997). In order to assess the long-term performance of alley cropping, Rao et al. (1997) reviewed the results of 29 trials, mostly with small plots, conducted for four or more years over a wide range of soils and climates across the tropics. The results showed both positive and negative effects of alley cropping on crop yields. In the semiarid sites, only two of ten studies gave substantial yield increases. In subhumid environments, significant positive yield responses were observed in seven out of eleven studies while in the humid tropics, maize and taro did not benefit from hedgerow intercropping in four out of eight trials, though bean and cowpea yields invariably increased.

Low biomass production of the hedgerow tree species (2 to 3 Mg/ha/yr) and competition of hedgerows for water with crops are the major drawbacks limiting the potential of prunings to improve fertility and productivity of soils in the water-limited areas (Ong et al. 1991; Rao et al. 1991; Mathuva et al. 1997; Mugendi et al. 1997). Inadequate water limited the response of crops even though alley cropping improved soil fertility in certain sites of the semiarid tropics. In such cases, a biomass transfer (cut-and-carry) system has been proposed as a more beneficial system than alley cropping (Jama et al. 1995). The system involves

planting agroforestry trees outside the crop fields to avoid competition between crops and trees. The trees are regularly pruned and the resulting biomass transferred and applied as a source of nutrients to the crops on separate fields.

Alley cropping has been shown to produce higher yields than sole-crop systems over a long period in acid soils of Indonesia and Peru (Nair et al. 1997). Many studies have indicated the reduction of Al toxicity with the addition of large amounts of organic residues because their decomposition products bind Al and reduce Al saturation thereby reducing soil acidity (Wong et al. 1995).

Improved Fallows

Sequential systems using planted tree fallows have not received the same level of attention as alley cropping, but the few studies undertaken illustrate the positive effect of tree fallows on crops. Short-duration fallows with herbaceous legumes have been found to increase yields of subsequent crops compared with grass fallows or continuous cropping systems (Noordwijk and Purnomosidhi 1995; Drechsel et al. 1996). However, tree fallows have distinct advantages over herbaceous fallows, particularly in seasonally dry climates, because they may take up nutrients from deep soil layers and recycle them better (Szott et al. 1994); furthermore, leguminous tree fallows may add nitrogen to the system through BNF.

In Zambia, one-year-old sesbania (*Sesbania sesban*) fallows increased the yield of subsequent maize by 50% to 80%, and two-year fallows by 150% to 270% over the control maize yields after a grass fallow or continuous cropping (Kwesiga and Coe 1994; Torquebiau and Kwesiga 1996). The residual effect of both one- and two-year fallows was observed even four years after clearing the fallow, with three times higher yield than in monocropped maize (Kwesiga et al., 1997). Such a large residual effect more than compensates for the loss of production during the fallow period. In western Kenya, 18 months of sesbania fallow produced in subsequent three seasons 9.7 Mg/ha of maize compared with 6.9 Mg/ha after a grass fallow and 4.9 Mg/ha after continuous maize cropping. The fallow effect at this P-deficient site was substantially higher after applying P fertilizer to maize (Jama et al. 1997b).

Based on such promising results, "improved fallows" is now being promoted as a promising technology for soil improvement in (ICRAF 1997) and it relies heavily on the nutrient-cycling capability of the shrubs and trees that are used during the short-rotation fallows.

Trees in Cropland (Parkland) Systems

"Trees in croplands", of which the 'parkland system' of West Africa (Saka et al. 1994) is a good example, involves scattered or dispersed trees such as *Faidherbia albida*,

Parkia biglobossa, vitelleria paradoxa, Melia volkensii, and *Azadirachta indica*. Trees in this system are rarely planted, but are derived from natural regeneration, and their stand density varies considerably (Nair et al. 1997). Reported yield increases under *Faidherbia albida* are maize by more than 100% in Malawi (Saka et al. 1994), and 76% in Ethiopia (Poschen 1986); and sorghum (*Sorghum bicolor*) by 36% in Ethiopia (Poschen 1986) and 125% in Burkina Faso (Depommier et al. 1992). The yield increases under faidherbia (often referred to as the 'albida effect') are attributed to the combined effects of improved soil fertility, soil water retention and microclimate amelioration (Nair et al. 1997).

Crop yield declines, relative to yields in open, treeless fields, were noted mostly under the canopies of large, evergreen, unmanaged trees. In Burkina Faso, sorghum yields under *Parkia biglobossa* and *Vitelleria paradoxa* trees were reduced on average by 50% and 70% respectively (Kessler 1992). Sorghum yields were reduced by up to 60% under canopies of both these species in southern Mali (Kater et al. 1992). In India, wheat yields were reduced by up to 60% (Puri and Bangarwa 1992) and mustard (*Brassica* spp.) yields by up to 65% (Yadav et al. 1993) under *Acacia nilotica* trees. Obviously, detailed analyses of the effect of site-specific factors are essential before generalizations can be made. But, it seems that if tree-shade conditions can be managed (either naturally because of the "reverse-phenology"

of the *Faidherbia albida* trees or deliberately as in the case of managed canopies of *Parkia biglobossa* and *Vitelleria paradoxa* trees), tree-mediated soil-improvement is an important factor that can support crop productivity in the parkland systems.

Tree Biological Dinitrogen Fixation

Though there are lots of discussions on the role of BNF in soil fertility maintenance in tropical agroforestry systems, the amount of N fixed and the extent to which it is used by the associated crop is not known. Some early reports on alley cropping trials claimed that enormously large quantities of N were fixed by some fast-growing tree species, especially *Leucaena leucocephala* and *Gliricidia sepium* (e.g., 100 to 300 kg--and sometimes up to 500 kg--N/ha/yr, as cited by Sanginga et al. 1995). But such estimates are subject to a number of variables such as soil, climate, and plant management conditions. Furthermore, high variability exists among provenances or isolines of nitrogen fixing trees (NFT) in the percentage of total plant N derived from atmospheric N_2 (% Ndfa) (Sanginga et al. 1995; 1996). Another problem is the difficulty in assessing the extent to which the N_2 fixed by NFTs becomes available (N recovery rates) to crops that are associated with the NFTs during current and subsequent seasons. This factor is inseparably mixed with the rate of organic matter

decomposition and N mineralization. To complicate the issue further, little is known about the effects that management practices, such as hedgerow pruning, can have on N_2 fixation. Thus, although it is a fact that some of the NFTs used in alley cropping are active N_2 fixers, the extent and time sequence of benefits derived under actual field conditions by using such species as hedgerows in alley cropping is not clearly understood. Other agroforestry systems where BNF plays an important role in maintenance of soil fertility include 1) shaded perennial systems where as much as 60 kg N/ha/yr have been estimated fixed by *Erythrina poeppigiana* in the coffee plantations (Fassbender et al. 1991), 2) parkland systems, where the extent of nitrogen fixation is not clearly known (most discussions agree that the soil fertility improvement by trees in these systems results from the cumulative benefits of several factors such as BNF, nutrient cycling, and nutrient accumulation under trees via excreta from animals and birds (Nair et al. 1997)), 3) mixed planting of leguminous and nonleguminous trees, e.g., *Eucalyptus* and *Acacia* spp. in short rotation industrial plantations (Panday 1995; Khanna and Foelster 1997), 4) sequential agroforestry systems and especially improved fallows where fast-growing species like *Sesbania* spp. *Cajanus cajan*, *Leucaena* spp. and *Tephrosia* spp. are used (Kwesiga and Coe 1994).

Though NFTs are a valuable resource in agroforestry systems, the extent to which the fixed N is actually used by the associated crop during its growth cycle versus the amount that goes into the soil's N pool for eventual use by subsequent crops is not known.

Decomposition and Mineralization of Tree Biomass

One of the major recognized avenues of soil fertility improvement in tropical agroforestry systems is the recycling of nutrients through decomposition of tree biomass that is added to the soil, mainly as fallen leaf litter or added/incorporated prunings, but also in the form of tree root biomass. Decomposition of these materials and the release of the nutrients contained in them are determined by the "quality" of the material, the environment, and the decomposer organisms present (Swift et al. 1979).

The "quality" of an organic material refers to its (organic) constituents and nutrient content (Cadisch and Giller 1997; Mafongoya et al. 1997a). The importance of the organic (carbon) constituents is that the availability of energy for decomposer organisms depends on the proportion of soluble carbon, cellulose and hemicellulose, and lignin. Soluble carbon includes metabolic and storage carbon, and is primarily responsible for promoting microbial growth and activity (Smith 1994). Green foliage usually contains 20% to 30% (dry matter basis) soluble carbon. Cellulose and

hemicellulose, which constitute 30% to 70% of plant carbon (12% to 30% of total plant material), are the structural polysaccharides, and are of "intermediate" quality; they are attacked by the decomposer microbes after soluble carbohydrates have been depleted (Swift et al. 1979). Lignin, which intertwines the cell wall physically protecting cellulose and other cell wall constituents from degradation (Chesson 1997), is of lowest quality, providing little or no energy to the decomposers until the last stages of decomposition. Thus, the lignin content of the material is considered to be the most important factor determining the rate of decomposition (Jama and Nair 1996; Mafongoya and Nair 1997; Mafongoya et al. 1997a). Lignin content of agroforestry tree species varies from 5% to 20% in green foliage and 10% to 40% in leaf litters (Constantinides and Fownes 1994). It has been suggested that 15% is a critical level, above which decomposition is impaired (Palm 1995).

Many recent studies with agroforestry tree species have shown that polyphenols, which comprise a relatively small percentage of the organic material have a disproportionately negative influence on decomposition and nitrogen release (Handayanto et al. 1994; Mafongoya et al. 1997a;b). Although polyphenols can serve as a carbon substrate for decomposers, they, in general, inhibit the growth or function of decomposers (Swift et al. 1979). Condensed tannins, also known as proanthocyanidins, are the polyphenols most noted

for their inhibitor effects on decomposition and nitrogen release. Some condensed tannins are soluble in polar extractants, while others are insoluble and bound to protein or the cell wall (Jackson et al. 1996). The effect of the bound condensed tannins (insoluble) is similar to that of lignin: they make the cell wall and proteins physically or chemically inaccessible to decomposer organisms and thus slow decomposition. In general, total soluble polyphenol content of green foliage of agroforestry species can be as high as 10%, but is usually less than 5% (Constantinides and Fownes, 1994). There is no apparent correlation between total polyphenols and condensed tannins. Some species such as *Senna siamea* have a fairly high total soluble polyphenol content (Constantinides and Fownes 1994) but a very low level of condensed tannins (Jackson et al. 1996), whereas *Calliandra calothyrsus* has high levels of both fractions (Handayanto et al. 1995).

In addition to the carbon quality, nutrient--especially nitrogen--content of plant materials is a major determinant of litter quality. Generally, materials with N content higher than 20 mg/g are considered to be of high quality, although this can be modified by lignin and polyphenol contents (Mafongoya et al. 1997a;b).

Several recent studies have related the rate of biomass decomposition with a number of these plant (litter)-quality indices. These include ratios of C to N, polyphenol to N,

lignin to N, and polyphenols + lignin to N (Palm 1995; Jama and Nair 1996; Mafongoya et al., 1997b). All of these are valid indicators, but each has its own advantages and disadvantages (Mafongoya et al. 1997a).

Multipurpose trees used in agroforestry systems vary widely in their chemical quality factors described above, and perhaps therefore, the decomposition characteristics of their biomass. Apart from these inherent quality variations among species, other factors such as the methods of analyses and plant parts used also make comparisons among decomposition data difficult. Nevertheless, it is possible to make reasonably accurate predictions on decomposition rates of plant materials that are commonly used in agroforestry systems. Mafongoya et al. (1997a) summarized these for a number of agroforestry species and concluded that species with leaves that are high in N, low in lignin, and low in polyphenols (e.g., *Gliricidia sepium* and *Sesbania* spp.) will decompose fast and release a large proportion of their N. Species that contain well lignified leaves (e.g., *Dactyladenia barteri* and *Flemingia macrophylla*) will decompose slowly and may cause immobilization of soil N for a fairly long period (several weeks). Decomposition of biomass of species with high N and polyphenol contents may be governed by their protein binding capacity: species such as *Leucaena leucocephala* with low protein binding capacity decompose rapidly, whereas those with high protein binding

capacity (e.g., *Calliandra calothyrsus*) decompose slowly. Furthermore, even species with narrow C to N ratio and low lignin and polyphenol contents may decompose slowly if large amounts of N are bound to condensed tannins as in the case of *Senna* (syn. *Cassia*) *siamea*. Thus, the large variations in decomposition patterns of several agroforestry species reported from a wide variety of situations can largely be interpreted based on the chemical quality parameters of the materials, and this information is now being used for making appropriate management decisions (Nair et al. 1997).

Management of Decomposition and Nutrient-Use Efficiency

In agroforestry systems, biomass decomposition can be "manipulated" to improve the efficiency of uptake and utilization of nutrients by growing plants. Mafongoya et al. (1997c) suggested two strategies for this: (1) regulate the rates of release of nutrients to improve the synchrony of nutrient supply with crop demand and (2) provide a more favorable environment for plant growth. While the former is of "immediate" (short-term) nature, the latter involves longer-term improvements often mediated through improvements in soil organic matter status (Nair et al. 1997).

Plant biomass that is available for decomposition in agroforestry systems usually involves green foliage as opposed to senescent material (litter) that dominates the biomass input in natural and agricultural systems. Because

mobile nutrients are retranslocated from maturing and senescent leaves to other plant parts before litterfall, litter differs from green foliage in quality and therefore decomposition rates (Constantinides and Fownes 1994). Conditions prevailing during tree growth can also result in plant biomass of differing quality. Nitrogen limitation, in particular, can enhance concentration of polyphenols in leaves. For example, Handayanto et al. (1995) produced litters of *C. calothyrsus* and *G. sepium* of widely varying quality by altering N supply to plants. Increased N concentration and reduced polyphenol concentration in leaves consequent to enhanced N supply to the plants resulted in faster decomposition and uptake of released N by maize (Handayanto et al. 1997). These results indicate that higher N_2 fixation by trees could result in production of better-quality tree-leaf biomass compared with biomass from trees growing under N-starved conditions. Field management operations that can alter biomass quality include duration and temperature of drying the material before applying it to the soil (fresh prunings decompose faster than sun-dried prunings), physical size of the material (smaller-sized or ground materials decompose faster than larger and coarser materials), mixing of biomass of differing compositions, and method of incorporating them (soil incorporation of materials results in faster decomposition, compared with surface placement) (Mafongoya et al. 1997b;c).

A major issue in the use of tree biomass as a source of nutrients for crops is ensuring the release of nutrients from decomposing biomass is effected at a time coinciding with the major nutrient uptake by crops (synchrony) (Swift 1987). Improved synchrony implies that the chances for loss of nutrients are minimized and thereby nutrient-use efficiency is enhanced (Myers et al. 1994). Better synchrony may be achieved by manipulating the crop's demand through adjustments of time of planting and crop selection, as well as nutrient release through altering biomass management options described earlier.

An important point to consider in this context is the extent to which the nutrients that are released from biomass decomposition, just as in the case of BNF, are taken up by the current (and subsequent) seasons' crops, usually referred to by the term "nutrient recovery". Many leguminous tree species used in agroforestry systems, especially alley cropping and biomass transfer systems, are capable of producing and recycling substantial quantities of biomass containing nutrients, with the notable exception of phosphorus, in quantities sufficient enough to support crop growth (Palm 1995). However, the reported rates of nutrient recovery by the current season's crop from decomposing tree biomass are highly variable, and in general, low (from about 5% to about 40%) (Haggar et al. 1993; Handayanto et al. 1994; Mugendi et al. 1994b; Palm 1995; Mafongoya and Nair

1997). Most of the nutrients in the applied biomass (as much as 80% N) are reportedly left in the soil organic pool (Haggar et al. 1993; Becker et al. 1994a), indicating that the benefit from input of tree biomass into crop production is more in terms of long-term accumulation of soil organic matter (SOM) and soil fertility than short-term gains such as provision of nutrients to benefit the current crop.

Tree Uptake of Nutrients from Deeper Soil Layers

Tree roots extend deep into the soil, beyond the rooting depth of common agricultural crops (Stone and Kalisz 1991). Recent research on agroforestry trees has focused on this deep-rooting attribute of trees with a view to understanding the spatial distribution and temporal patterns of root growth (Ruhigwa et al. 1992; Noordwijk et al. 1996) and relating such information to nutrient uptake by tree roots from deeper soil layers (Mekonnen et al. 1997; Buresh and Tian 1997).

Researchers in western Kenya's acid soils (Kandiudalfic Eutrudox) have noted accumulation of fairly large quantities of nitrate (70 to 315 kg N/ha) at 0.5-to-2.0 m-depth under unfertilized maize in farmers' fields, and attributed it to formation of nitrate by mineralization of SOM and its sorption and retention by clay minerals (Mekonnen et al., 1997). Fast-growing trees such as *C. calothyrsus*, *S. sesban*, and *E. grandis* grown in rotation with maize rapidly rooted

into this nitrate-reserve zone and took up the sorbed nitrate that was inaccessible to maize (Hartemink et al. 1996; Jama et al. 1997a). Nitrate-N to 4-m depth was only 51 kg N/ha in a 15-month *S. sesban* fallow, as compared to 199 kg N/ha in unfertilized maize soil. The maximum rooting depth was 1.2 m for maize, whereas roots of 15-month-old *S. sesban* extended to below 4 m (Mekonnen et al. 1997). Recent review in this area by Buresh and Tian (1997) concluded that the potential of trees to take up subsoil nutrients is generally greatest when the trees have deeper root systems, and a high demand for nutrients, when there is water and/or nutrient stress in the surface soil, and when considerable reserves of plant-available nutrients or weatherable minerals occur in the subsoil. Greater uptake from deeper soils could be expected for water-soluble nutrients such as nitrate and much less for immobile nutrients such as P.

Trees with their deep-rooting abilities can, therefore, take up nutrients from deeper soil layers that are beyond the rooting depth of most agricultural crops thereby recycling nutrients that would otherwise be lost from the system. The role of trees in nutrient uptake from deeper soil layers for nutrients other than N and P is, however, very little studied.

The results reviewed here can be taken as representative of major agroecological/geographical zones as categorized by Nair (1992): hedgerow intercropping (at

least, those for which favorable results have been obtained) for humid and subhumid tropical lowlands with seasonal rainfall, parklands systems for the semiarid regions, and improved fallow systems for the humid lowlands. In all these systems, there are encouraging examples to indicate that agroforestry systems can meet the nitrogen requirements to sustain crop production, albeit at low levels. Where, the objective is maximum production, supplementation with inorganic fertilizers will be essential.

CHAPTER 3
PRODUCTIVITY OF MAIZE ALLEY CROPPED WITH CALLIANDRA AND LEUCAENA

Introduction

In many parts of the tropics and particularly in tropical Africa, N is the most limiting nutrient to crop production. High costs of inorganic fertilizers limit their use by most smallholder farmers (FAO 1989). This has led to increasing interest in the development of integrated soil fertility management systems that incorporate woody species (especially N_2-fixing legumes) in the crop production systems (Kang et al. 1990). Leafy prunings from these woody species are utilized for the provision of N to interplanted annual crop (Kang et al. 1990; Xu et al. 1992).

The central highlands of Kenya are amongst the most densely populated regions in Kenya with more than 500 persons/km^2 (Government of Kenya 1994). Declining crop yield has been a major problem facing smallholder farmers in this region. The major factor contributing to reduced productivity is soil impoverishment caused by continuous cropping without addition of adequate fertilizers and manures (Minae and Nyamai 1988). Development of improved

agricultural technologies that allow for increased food production are, therefore, necessary.

With this background, a project was initiated in 1992[1] in Embu (one of the districts in the region) with the aim of developing agroforestry technologies for this area. The study results reported in this dissertation were a part of this project. The focus of the study was to evaluate the potential contributions of selected multipurpose agroforestry tree species to alleviation of the above-stated constraint of declining soil fertility. The selected tree species were *Calliandra calothyrsus* Meissner (calliandra) and *Leucaena leucocephala* (Lam.) De Wit (leucaena) which had been identified as two of the most appropriate species for soil improvement and crop sustainability through agroforestry research at Maseno, Kenya (Heinemann et al. 1990), which is agroecologically similar to Embu District.

Materials and Methods

Experimental Site

The experiment was conducted at the Embu Regional Research Centre, Eastern Province, Kenya. The Centre is located in the central highlands of Kenya on the south

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[1] The project is a part of an on-going collaborative research by Kenya Forestry Research Institute (KEFRI), Kenya Agricultural Research Institute (KARI), and the International Centre for Research in Agroforestry (ICRAF).

eastern slopes of Mt. Kenya at 0° 30'S, 37° 30'E and an altitude of 1480 m. The soils are mainly Typic Palehumult (Humic Nitisols according to FAO-UNESCO) derived from basic volcanic rocks. They are deep, well weathered with friable clay texture with moderate to high inherent fertility (Table 3.3). Total annual average rainfall is 1200 mm to 1500 mm received in two distinct rainy seasons: the long rains (LR) from mid March to June with an average precipitation of 650 mm and the short rains (SR) from mid October to December with an average of 450 mm. The average monthly maximum temperature is 25°C and the minimum 14°C. The long term monthly average is 19.5°C. Climatic descriptors and soil properties for the study site are presented in Tables 3.1 and 3.3 respectively.

Both N and P had been determined to be the most limiting nutrients to crop growth in the region (FURP 1987). When the general project, upon which this study was based, was formulated, it had been decided that the main objective of the investigations was to address N deficiencies and that all the experimental plots should receive recommended basal applications of P fertilizer (50 kg P/ha) whenever P deficient symptoms appeared. The rationale for this decision was based on the fact that tree leafy-biomass incorporated into the soil contained very little P content (compared to N) which would not meet the P requirements of the associated maize crop.

Table 3.1. Climatic descriptors of the experimental site at Embu, Kenya.

	Rainfall (mm)				Temperature (°C)					
Month	Avg†	1994	1995	1996	1994		1995		1996	
					Max	Min	Max	Min	Max	Min
Jan	26	0	7	52	25.6	13.1	25.3	13.3	24.9	13.4
Feb	29	0	119	14	27.9	14.0	26.9	13.7	26.9	13.7
Mar	123	55	167	165	27.7	14.6	25.4	15.1	27.0	15.5
Apr	320	444	349	130	25.3	15.6	24.9	15.6	25.9	16.0
May	170	202	119	185	24.1	15.1	24.1	15.9	24.5	15.7
Jun	35	17	11	52	23.1	14.1	21.9	13.0	21.3	14.3
Jul	78	55	19	35	21.4	13.6	21.4	13.1	24.4	16.9
Aug	67	33	71	19	22.1	13.1	22.0	13.5	25.0	14.0
Sep	43	30	64	0	25.4	13.4	24.8	13.9	24.8	13.1
Oct	194	245	277	13	25.2	15.1	23.9	14.7	26.5	14.3
Nov	195	436	221	242	23.7	14.5	23.7	14.5	23.1	14.5
Dec	61	57	99	1	23.5	13.2	23.6	13.2	24.5	12.5

†Represents average long term rainfall for > 20 years.
Source: O'Neill et al. (1995).

Cropping History

The area had been cropped with maize-bean rotations for several years before it was left fallow for two seasons prior to its allocation to the agroforestry project in June 1991. Before setting up the experiment, uniformity trials of maize (*Zea mays* L.) (Hybrid 511) were conducted without fertilizer application during the SR 1991 and LR 1992 seasons which revealed the land to be fairly uniform in terms of soil fertility. Analysis of soil sampled at the end

of 1991 SR season indicated no significant differences among different blocks, confirming the uniformity of soil fertility among the blocks (O'Neill et al. 1993).

Experimental Treatments

The experiment was composed of ten treatments. The test crop, maize, was grown alone or alley cropped with or without fertilizer/prunings application, as detailed below:

Alley cropping; no fertilizer
1) *C. calothyrsus*; prunings incorporated
2) *L. leucocephala*; prunings incorporated
3) *C. calothyrsus*; prunings not incorporated
4) *L. leucocephala*; prunings not incorporated

Maize only; no alley cropping; prunings from outside incorporated
5) *C. calothyrsus* prunings + no fertilizer
6) *L. leucocephala* prunings + no fertilizer
7) *C. calothyrsus* prunings + fertilizer
8) *L. leucocephala* prunings + fertilizer

Maize only; no alley cropping
9) With fertilizer
10) Without fertilizer

Experimental Layout

The experimental design was a randomized complete block with four replicates. The layout of the plots is presented in Figure 3.1. The plot dimensions were 9 m x 10 m. The inter- and intra-row spacing for calliandra and leucaena trees was 4.5 m and 0.5 m, respectively. Between hedgerows, six rows of maize were grown at a spacing of 75 x 25 cm (two maize seeds planted per hill/hole but later thinned to

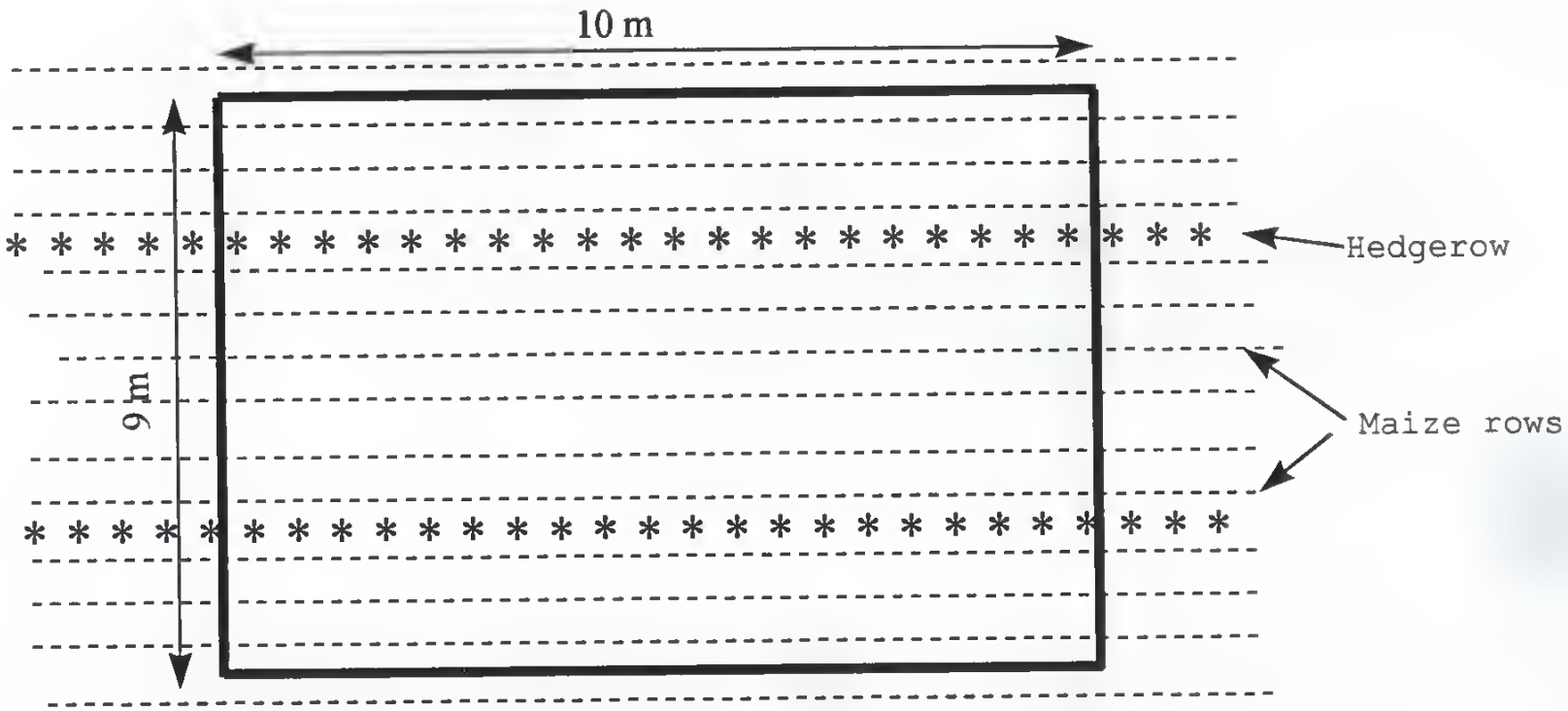

Figure 3.1. Plot layout of the alley cropping experiment at Embu, Kenya

one/hill after four weeks). The trees were planted in April (LR) 1992 and the application of experimental treatments started in the LR 1993 season.

Lopping of Tree Hedges and Prunings Incorporation

Lopping of calliandra and leucaena tree hedges was done one to two days before maize was planted. Hedges were lopped at a height of 50 cm using sharp knives. Leafy biomass and succulent stems were separated from hardened stems (removed for firewood) and each weighed separately. The leafy biomass was then chopped into smaller pieces (5 to 10 cm), evenly spread on the ground over the plot area and soil-incorporated using hand hoes into the plots that received prunings (Table 3.2) as the land was prepared for maize planting. Leafy biomass applied in treatments 7 & 8 (that received prunings from outside the experimental plots) were obtained from block plantings of calliandra and leucaena hedges near the site. The weight of prunings applied to Treatments 5 & 7, and 6 & 8 was equal to the weight of prunings obtained from Treatments 3 & 4, respectively.

Root Pruning (Trenching)

Root pruning was done at the beginning of each growing season to curb roots extending to the neighboring plots. Trenches of approximately 1 m deep and 0.3 m wide were dug between plots with hedges and adjacent plots. Roots along

Table 3.2. Amount of soil-incorporated tree-biomass and their N contribution into the soil in the 1994-96 seasons at Embu, Kenya.

Trt	AC/PI/NF†	SR 94	LR 95	SR 95	LR 96	Biomass	Mean N
		Tree biomass in Mg/ha/season				Average Mg/ha/season	kg/ha/ season
1	C/C/-	2.6	1.1	2.3	1.5	1.9	56
2	L/L/-	2.5	2.2	1.3	1.3	1.8	58
5	-/C/-	2.3	1.5	3.1	2.3	2.3	69
6	-/L/-	2.6	2.4	1.9	2.1	2.3	67
7	-/C/25	2.3	1.5	3.1	2.3	2.3	69
8	-/L/25	2.6	2.4	1.9	2.1	2.3	67

†AC - alley crop tree species (C = calliandra, L = leucaena)
PI - type of pruning incorporated (C = calliandra, L = leucaena)
NF - nitrogen fertilizer applied (kg N/ha)
Abbreviations: Trt = treatments; SR = short rain; LR = long rain.

these trenches were cut using a sharp knife. The trench was then covered with soil; the sub-soil was returned first followed by the top soil.

Fertilizer Application

Treatments 7 and 8 received 25 kg N/ha while Treatment 9 received 50 kg N/ha of Calcium Ammonium Nitrate (CAN) fertilizer applied through top dressing in two equal doses. The first dose was applied four weeks after maize germination and the second dose four weeks later. All the experimental plots received a basal application of P fertilizer at the recommended level (50 kg P/ha) once per year at the beginning of the long rain season (Season 1).

Sampling and Analyses

Soil was sampled (0 cm to 20 cm depth) before the experiment was initiated (February 1992) and both chemical and physical properties including bulk density and infiltration rate determined (Table 3.3) using the procedures outlined by Anderson and Ingram (1993). Nutrient analyses were done according to methods outlined in the ICRAF Laboratory Manual (1995). Soil water content was determined for the 0 cm to 20 cm depth in both seasons of 1995 using the Tropical Soil Biology and Fertility Handbook of Methods procedure (Anderson and Ingram 1993).

For plant analysis, random subsamples were taken from every plot before prunings were incorporated into the soil, washed with distilled water and oven dried at 65°C for 48 h. The same procedure was applied to maize stover, cob, and grain at harvest. Samples were ground progressively using 2 mm followed by 0.5 mm sieve mills. The resulting powder was thoroughly mixed, packed in polythene bags and stored under dry conditions before N was determined (ICRAF 1995).

Maize Harvesting

Net plots measuring 6 x 9 m dermacated in the middle of the total plots were harvested first. Only the six maize rows inside the two hedgerows were considered for purposes of data recording and maize yield determination (Figure

3.1). Harvesting was done by cutting the maize plants at the base. Maize cobs were manually separated from the stover, sun-dried, and packed in paper bags before threshing. After threshing, moisture content of the grains was determined using a moisture meter and grain weights adjusted to 12% moisture content.

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using SAS program (SAS 1988). Means were separated by Tukey's procedure and declared different at $P < 0.05$. Single degree of freedom contrasts were performed to compare maize grain yields from various treatments.

Results

Soil Changes

The site had a fairly uniform soil fertility at the beginning of the trial (Table 3.3), corroborating results on uniformity trials reported earlier (O'Neill et al. 1993). However, after four years of study (Table 3.4), a general decline in the soil nutrient levels was observed, with the greatest decline occurring in the treatments that did not receive prunings application. For example, total C declined by approximately 20% (from 2.2 to 1.8 g/100g) in the absolute control treatment (Trt 10) whereas the decline in the *ex situ* calliandra added prunings (Trt 5) was only 5%.

Table 3.3. Soil properties of the experimental site at Embu before commencement of the study (February 1992).

Trt‡	AC/PI/NF†	pH	Ca	Mg	K	P¶	C	N	BD	Clay	Sand	Silt	Infilt
			Exchangeable (cmol/kg)			mg/kg	g/100g		g/cm³	------- % -------			cm/min
1	C/C/-	5.8	6.8	2.8	1.0	9.3	2.2	0.24	1.1	39	29	32	0.9
2	L/L/-	5.7	7.0	2.6	0.8	6.8	2.2	0.24	1.1	40	32	28	0.9
3	C/-/-	5.9	8.0	2.9	0.9	8.8	2.2	0.25	1.1	38	35	26	0.7
4	L/-/-	6.0	7.6	2.6	1.0	9.8	2.2	0.26	1.1	39	32	29	0.8
5	-/C/-	5.5	5.6	2.0	0.6	8.0	2.0	0.24	1.1	36	32	32	1.0
6	-/L/-	5.8	7.2	2.7	0.8	7.3	2.1	0.24	1.2	37	34	29	1.0
7	-/C/25	5.9	7.6	2.3	1.1	10.3	2.1	0.24	1.1	37	31	32	1.0
8	-/L/25	5.5	7.0	2.2	0.7	6.5	2.1	0.24	1.1	38	31	30	1.0
9	-/-/50	5.7	7.4	2.2	0.9	8.5	2.0	0.23	1.1	39	31	30	0.7
10	-/-/-	5.9	7.5	2.7	0.9	10.3	2.2	0.25	1.1	36	33	31	0.7

‡All treatment means were not significantly different at $P < 0.05$.
†AC - alley crop tree species (C = calliandra, L = leucaena)
PI - type of pruning incorporated (C = calliandra, L = leucaena)
NF - nitrogen fertilizer applied (kg N/ha)
¶Available P.
Abbreviation: Trt = treatments.

Table 3.4. Soil properties of the experimental site at Embu after four years of study (February 1996).

Trt	AC/PI/NF†	pH	Ca	Mg	K	P¶	C	N	BD	Infilt
			Exchangeable (cmol/kg)			mg/kg	g/100g		g/cm³	cm/min
1	C/C/-	5.7 a	6.3 a	2.4 a	0.9 a	5.8 bc	2.0 a	0.25 a	1.0 a	1.8 a
2	L/L/-	5.6 ab	7.0 a	2.4 a	0.8 a	5.8 bc	2.0 a	0.26 a	1.0 a	1.4 ab
3	C/-/-	5.7 a	7.8 a	2.5 a	0.7 a	5.0 c	1.9 a	0.25 a	1.0 a	1.0 bc
4	L/-/-	5.8 a	7.5 a	2.4 a	0.8 a	6.8 ab	1.9 a	0.25 a	1.0 a	1.1 bc
5	-/C/-	5.4 ab	5.5 a	1.9 b	0.5 a	7.5 ab	1.9 a	0.26 a	1.1 a	1.2 ab
6	-/L/-	5.6 ab	7.0 a	2.2 ab	0.9 a	6.3 bc	1.9 a	0.26 a	1.1 a	1.3 ab
7	-/C/25	5.5 ab	7.5 a	2.3 ab	0.9 a	8.3 a	1.9 a	0.25 a	1.0 a	1.5 ab
8	-/L/25	5.3 ab	6.3 a	2.0 ab	0.7 a	8.5 a	1.9 a	0.26 a	1.0 a	1.1 bc
9	-/-/50	5.6 ab	7.4 a	2.4 a	0.7 a	6.5 ab	1.8 a	0.22 b	1.1 a	0.9 c
10	-/-/-	5.7 a	6.6 a	2.4 a	0.7 a	6.5 ab	1.8 a	0.24 ab	1.1 a	0.9 c

Means followed by the same letter within a column are not significantly different at $P < 0.05$.
†AC - alley crop tree species (C = calliandra, L = leucaena)
PI - type of pruning incorporated (C = calliandra, L = leucaena)
NF - nitrogen fertilizer applied (kg N/ha)
¶Available P.
Abbreviation: Trt = treatments.

Total soil N, however, increased in the plots that received prunings but declined in those that did not. The rate of infiltration was significantly higher in the treatments that received prunings.

Maize Yield

There were no significant differences in maize yields among the experimental treatments during the LR season of 1993 (first season after treatment initiation). There was a crop failure during the second season (SR) of 1993 due to insufficient rainfall. Maize seedlings were attacked by chauffeur grubs (*Heteronyclus* spp.) at germination during the first season (LR) of 1994 resulting in yields that were variable. The results for these three seasons are reported in O'Neill et al. (1994, 1995) and Mwangi (1996). The results reported here are for the second season (SR) of 1994 to the first season (LR) of 1996 (Tables 3.5).

Table 3.5 shows that maize alley-cropped with leucaena (Trt 2) produced higher yields than non alley-cropped (both fertilized (Trt 9) and non fertilized (absolute control--Trt 10) treatments; however, the yield of alley-cropped calliandra (Trt 1) was equal to or less than that of the absolute control. Both calliandra and leucaena treatments that received *ex situ* applied prunings without or with fertilizer (Trt 5 and 6, and Trt 7 and 8) produced the highest maize grain yields in all the seasons. The lowest

yields were obtained from the alley-cropped, prunings removed treatments (Trt 3 and 4).

Table 3.5. Maize grain yield for 1994-96 seasons at Embu, Kenya.

TRT	AC/PI/NF†	SR 94	LR 95	SR 95	LR 96	Mean
		----------	----------	Mg/ha/season	----------	----------
1	C/C/-	3.2 ab	3.4 b	2.4 e	2.0 c	2.7 d
2	L/L/-	3.8 a	4.4 a	3.9 bc	3.6 b	3.9 b
3	C/-/-	1.6 c	1.1 e	1.0 g	1.3 d	1.3 f
4	L/-/-	2.7 b	1.8 d	1.7 f	1.5 cd	1.9 e
5	-/C/-	3.6 ab	4.0 ab	4.9 a	3.8 b	4.1 a
6	-/L/-	3.3 ab	4.5 a	4.7 ab	3.9 ab	4.1 a
7	-/C/25	3.6 ab	3.2 cd	5.6 a	4.2 a	4.2 a
8	-/L/25	3.4 ab	3.6 bc	5.2 a	4.1 ab	4.1 a
9	-/-/50	3.1 ab	3.1 bc	3.5 c	3.6 b	3.3 c
10	-/-/-	3.0 ab	4.0 ab	3.5 cd	1.8 c	3.1 c

Means followed by the same letter within a column are not significantly different at $P < 0.05$.
†AC - alley crop tree species (C = calliandra, L = leucaena)
PI - type of pruning incorporated (C = calliandra, L = leucaena)
NF - nitrogen fertilizer applied (kg N/ha)
Abbreviations: TRT = treatments; SR = short rain; LR = long rain.

Competition

The rationale for establishing treatments 1 and 2 (maize alley crop, prunings applied *in situ*) and treatments 5 and 6 (maize monocrop, prunings applied *ex situ*) was to assess the competitiveness of the tree hedges when the maize grain yields from treatments 1 and 2 were subtracted from those of 5 and 6 respectively. The results showing yield

changes from these comparisons (single degree contrasts) are presented in Table 3.6. The results indicate that yields of calliandra alley-cropped maize (Trt 1) were 11% to 51% lower than those of nonalley-cropped treatments that received calliandra prunings from *ex situ* grown trees (Trt 5). The decrease was 2% to 17% with leucaena (Trt 2 vs 6), implying that calliandra hedges were more competitive than leucaena hedges. The competitiveness of calliandra tree hedges over leucaena hedges was further confirmed by graphically presenting the maize grain yields from various treatments above (or below) the yield of the absolute control treatment (Figure 3.2). It is observed from this figure that calliandra alley-cropped treatment (Trt 1) produced 0.4 Mg/ha less maize grain yields compared to the control whereas leucaena alley-cropped treatment produced 0.8 Mg/ha more yields than the control. It is, however, noted that, both calliandra and leucaena treatments that received *ex situ* prunings without or with fertilizer (Trts 5 and 6, and 7 and 8) produced yields that were not significantly different from each other in all the seasons (Table 3.5 and Figure 3.2), hence the resulting maize grain yield differences between calliandra and leucaena alley-cropped treatments was due to the fact that calliandra tree hedges were more competitive than leucaena hedges.

Table 3.6. Yield change from contrasts comparing alley-cropped prunings applied treatments with the *ex situ* prunings applied treatments at Embu, Kenya.

	SR 94	LR 95	SR 95	LR 96
Treatments†	---------- % increase (+) or decrease (-) ----------			
1 vs 5	-10.9	-15.8*	-50.7***	-47.6***
2 vs 6	+14.0	-2.1	-16.9**	-6.7

Level of significance: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.
†Treatments: 1. calliandra alley crop, prunings applied; 2. leucaena alley crop, prunings applied; 5. maize monocrop, calliandra prunings applied; 6. maize monocrop, leucaena prunings applied.
Abbreviations: SR = short rain season; LR = long rain season.

Maize Yield on a per Row Basis

The lowest maize grain yields on a per row basis for those treatment plots that had hedges *in situ* were recorded for the maize rows nearest the hedges (Table 3.7). The southern rows, however, recorded slightly higher grain yields than the northern rows in similar (identical distances from the hedge) positions (Figure 3.3).

Soil Water Content

It was observed that rows next to the hedges had the highest amount of soil water (Figure 3.4), with the amount decreasing towards the middle of the alley. It was also observed that treatments that had trees and/or prunings incorporated had a higher soil water content compared to those that did not, though the differences were not significantly different (data not shown).

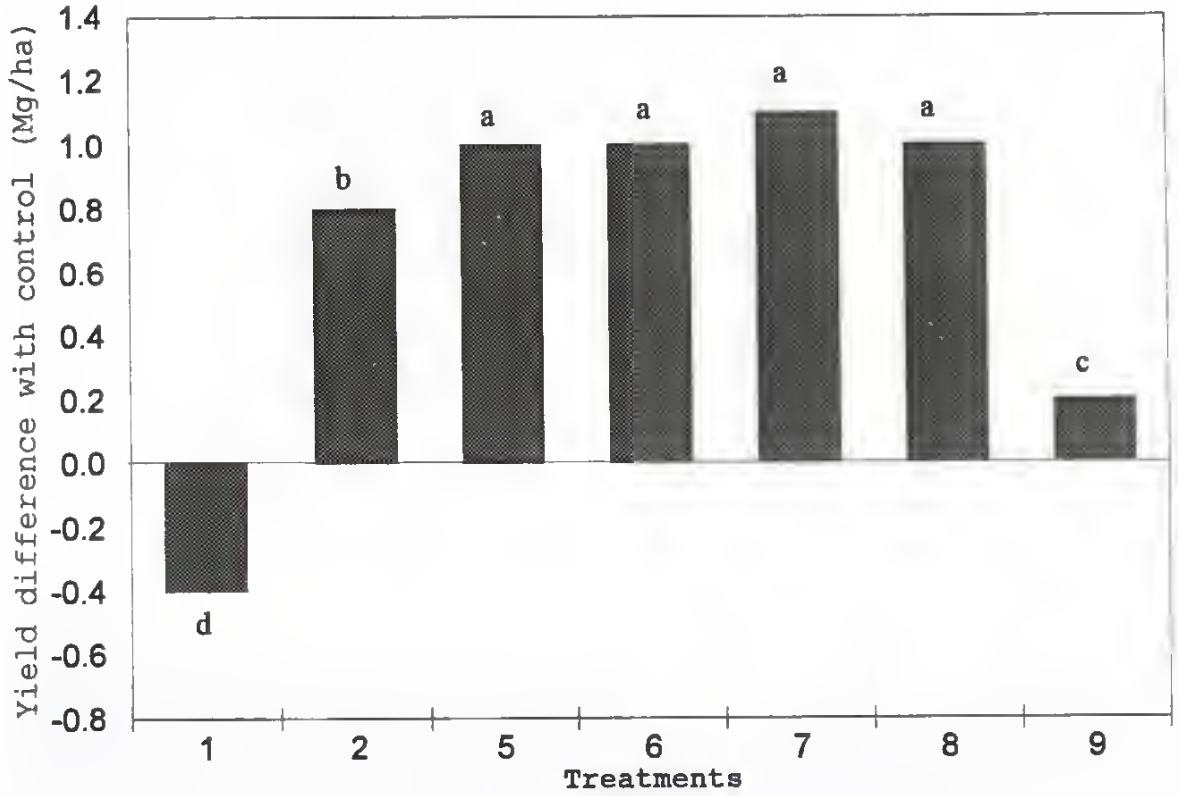

Figure 3.2. Average maize grain yield of various treatments in comparision with that of absolute control (Treatment 10) at Embu, Kenya (Treatment 1 & 2 = calliandra & leucaena alley crop; 5 & 6 = calliandra & leucaena monocrop + ex situ applied prunings; 7 & 8 = same as 5 & 6 + fertilizer; 9 = maize moncrop + fertilizer).

Table 3.7. Maize grain yield for different rows in the alley-cropped treatments at Embu, Kenya.

	Seasons (1994 - 1996), Maize yield kg/6 m row			
Row†	SR 94	LR 95	SR 95	LR 96
0.3 N	8.5 d	8.7 b	9.2 b	7.2 b
1.1	13.0 b	12.6 a	9.7 ab	7.4 b
1.8	13.9 b	13.6 a	10.0 ab	9.7 a
1.8	16.0 a	14.2 a	11.7 a	10.4 a
1.1	14.2 b	12.8 a	10.5 ab	10.0 a
0.3 S	10.8 c	10.5 b	9.8 ab	8.8 ab

Means followed by the same letter within a column are not significantly different at $P < 0.05$.
†Row position denoting distance (m) from the hedgerow between two hedges in N-S direction.

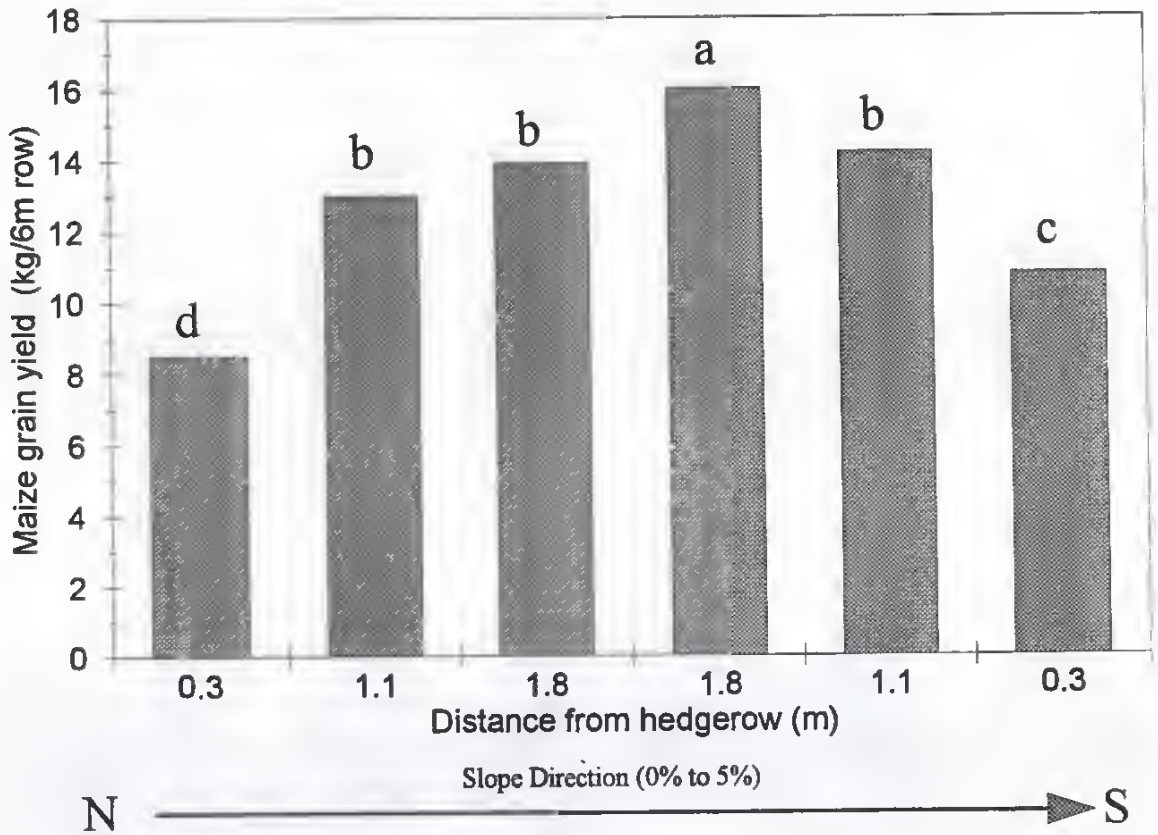

Figure 3.3. Influence of hedge distance on yield of alley cropped maize at Embu, Kenya in the long rain 1995 season. Bars with different letters are significantly different at $p<0.05$

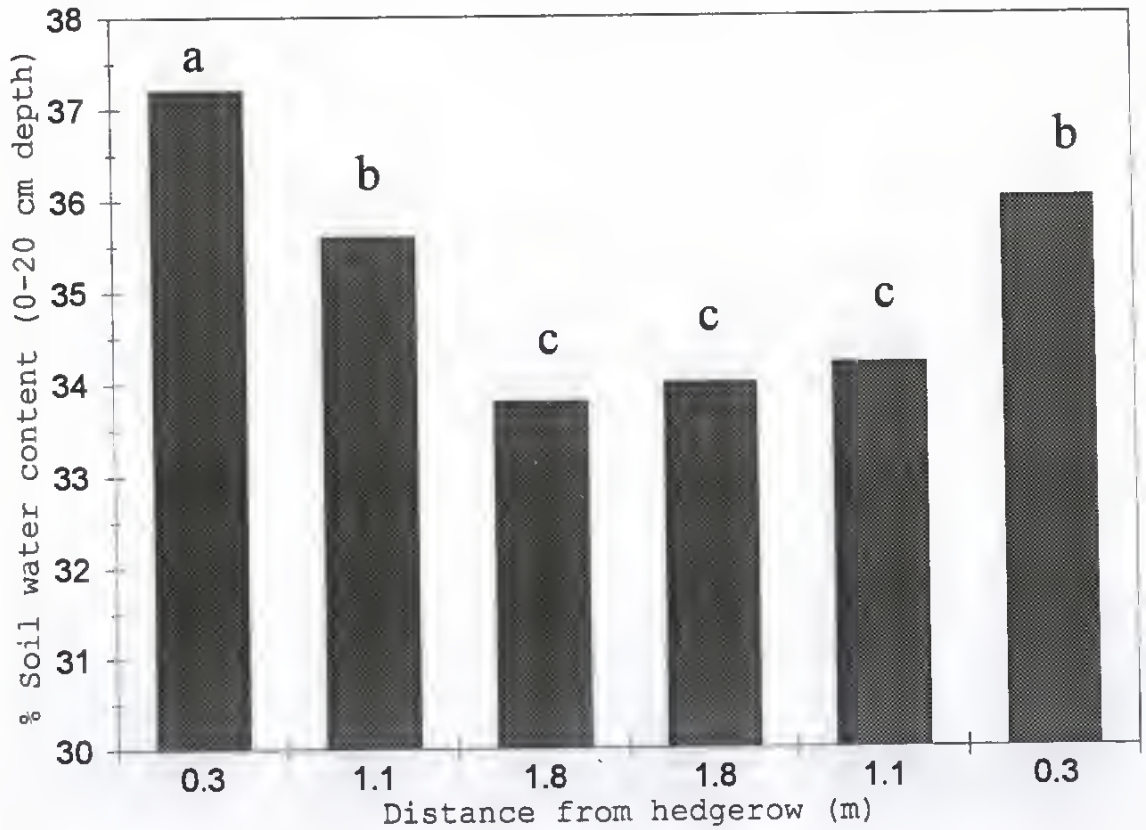

Figure 3.4. Soil water content (0 to 20 cm depth) under alley cropped maize rows at increasing distances from the hedgerows during the long rain 1995

Discussion

The amounts of prunings applied, ranging from 1.1 to 3.1 Mg/ha/season (3 to 5 Mg/ha/yr)(Table 3.2), did not contribute sufficient amounts of nutrients to compensate wholly for those lost through harvest. These results agree with those reported by others (Lal 1989; Kang 1993; Nair 1993; Schroth et al. 1995) where a smaller decline was observed in soil fertility parameters in the plots that had prunings applied compared to those that did not. These findings, however, do not agree with reports from the humid tropics where application of prunings to the soil resulted in increased soil organic matter and higher N, P, K, Ca, and Mg (Kang et al. 1985; Yamoah et al. 1986a; Kang et al. 1990; Tian et al. 1992, 1993). Whereas hedgerow tree species in the humid tropics produced 8 to 10 Mg/ha/yr of biomass (Young 1989), those in the subhumid tropics of Kenya produced only half of that amount. Young (1989) stated that low biomass production of hedgerow tree species in alley cropping systems is one major drawback that limits the potential of prunings to improve fertility and productivity of soils. The rate of infiltration was however, higher in the treatments that received prunings compared to those that did not. This finding corroborates the work of Jama et al. (1995) who observed that application of prunings to the soil improved soil-surface structure thereby increasing the rate of infiltration in an alfisol in the semiarid Kenya.

Hedges were pruned frequently and maintained at a low height (50 cm), so they did not pose any significant competition for light with maize plants during the growing season. The observed maize grain yield decrease in the treatments that had tree hedges *in situ* was therefore likely as a result of below ground competition between the maize crop and tree hedges. The competitiveness of calliandra tree hedges compared with leucaena's may be explained by the root morphology of the two species. Calliandra trees develop strong superficial root system in addition to the tap root (NAS 1983). Jama et al. (1997a) demonstrated that calliandra had the highest root density in the top 0 to 15 cm compared to four other multipurpose tree species that were included in their study in an oxisol in the subhumid highlands of western Kenya. On the other hand, leucaena has a deep tap root system and develops very few lateral roots which usually grow downward at a sharp angle (NAS 1977). After an initial moderately rapid establishment phase with some horizontal roots in the top soil, most of leucaena's later root development tend to be confined in the lower levels of the soil (Noordwijik et al. 1996). Govindarajan et al. (1996) observed a lower leucaena root density in the 0 to 12.5 cm soil depth compared to maize roots in an alfisol in semiarid Machakos, Kenya. However, at soil depth below 75 cm, the root density of leucaena increased over that of maize. The superiority of leucaena alley-cropped treatments

over those of calliandra may therefore be explained by calliandra hedges being more competitive with maize than leucaena hedges. Note that, when prunings from both species were applied *ex situ* (Trt 5 and 6) the yields obtained were not significantly different from each other throughout all the seasons (Table 3.5).

Leucaena can be used effectively in alley cropping arrangements to improve crop yields (Mulongoy and Meersch 1988; Palada et al. 1992; Kang 1993; Xu 1993). However, researchers working with calliandra have reported mixed performance; some indicted that it was able to improve crop yields (Heinemann et al. 1990; Rosecrance et al. 1992), while others reported depressed or marginal increases in crop yields (Gutteridge 1992; Mugendi et al. 1994b). The unfavorable results have been explained by the complicated chemistry of high concentrations of polyphenols in calliandra leaves that seem to hinder N release when the materials decompose (Handayanto et al. 1994; Mafongoya et al. 1997a). However, in the present study, this does not seem to be the case since calliandra treatments that had no hedges (Trt 5 and 7) produced yields that were not different from those of similar leucaena treatments (Trt 6 and 8).

Treatments that received prunings supplemented with 50% of recommended level of inorganic N fertilizer (Trt 7 and 8) produced higher yields than all other treatments during the last two seasons of the study (SR 95 and LR 96). Nitrogen-

utilization efficiency (recovery rate) in prunings has been shown to range from 5% to 40% (Mulongoy and Meersch 1988; Gutteridge 1992; Palada 1992; Mugendi et al. 1994b; Giller and cadisch 1995; Jama et al. 1995; Palm 1995; Mafongoya and Nair 1997), hence to achieve maximum maize yield, additional inorganic fertilizer is often required.

It was evident from the results on per row maize yield that for the treatments with hedges *in situ*, yields declined nearer the hedges (Table 3.8 and Figure 3.3). Similar results were observed by Yamoah et al. (1986b) and Smucker et al. (1995) who attributed this phenomenon to root competition because of higher densities of fine roots nearer the hedgerows. The decline was consistently higher on the northern part of the hedge as compared to the southern side. This could be attributed to the gentle slope (5%) that runs in a N-S direction. The hedges act as barrier for water, soil, and nutrients thereby benefiting the southern maize rows immediately above the hedge. Similar observations were made by Sang and Hoekstra (1987) and Smucker et al. (1995). They attributed these differences to downward movement of water and nutrients due to sloping terrain benefiting the crop at the lower level immediately above the hedge. Profiles of soil water content observed in different row positions showed the rows next to the hedges had the highest amounts of water (Figure 3.4). The decrease in grain yields observed in the maize rows nearest the hedges could

therefore not be attributed to competition for water. This seems to suggest that below ground competition was principally for nutrients.

Despite the promising results shown of alley cropping technology, the question of labor availability needs to be addressed properly before a wide adoption by farmers can be envisaged. The technology is labor-intensive with much of the demand for labor occurring during the rainy season which is the busiest time of the year (Nair 1993). Additional labor for persons already fully occupied at peak labor seasons is considered more costly than when additional demands come during slack periods. The cost of production will increase considerably if additional labor must be hired (Hoekstra 1987). Although the additional labor costs may be offset by increased yields, the immediate need for additional labor could be a disincentive to the adoption of the technology (Kang et al. 1990).

Results from this study indicate that alley cropping with leucaena is advantageous in the subhumid highlands of Kenya. On the other hand, inclusion of calliandra hedges on cropland adversely affect crop yields at least in the short term. Though calliandra had been recommended as a key species due to its satisfactory performance in alley cropping trials in the western highlands of Kenya (which are agroecologically similar to central highlands), its performance in the central highlands of Kenya was not

satisfactory, confirming the suggestion that alley cropping results are location-specific and generalizations may be difficult. The long term effects of alley cropping in these conditions are not known. The current experiment will need to be extended for a few more years to investigate long term effects.

CHAPTER 4
SYNCHRONY BETWEEN SOIL N MINERALIZATION AND N UPTAKE BY MAIZE FOLLOWING BIOMASS APPLICATION

Introduction

In many tropical agricultural systems with limited access to fertilizers, tree biomass is often used to meet the N requirements of annual crops. The biggest challenge in this approach is that of achieving synchrony between the N released from decomposing biomass and the demand (uptake) by the crop (Swift 1987). Synchronization of N supply and N demand will lead to increased N-use efficiency of the incorporated biomass (Becker et al. 1994a). In order to manage the short and long term N availability to crops with organic inputs, N mineralization and immobilization patterns need to be understood. These in turn depend to a large extent on chemical composition of plant tissues (Swift et al 1979; Constantinides and Fownes 1994). Initial N content of the biomass, C:N ratio, lignin content, lignin:N ratio, and polyphenol and its ratios with N and lignin have been shown to be important chemical qualities affecting the rate of decomposition and mineralization (Palm 1995; Mafongoya et al. 1997a). Other factors that affect the rate of mineralization include soil characteristics and cultural

practices such as the method of application of biomass, application of mineral fertilizers and methods employed in soil tillage (Becker et al. 1994b).

The objective of this study was to investigate the rate of mineralization of soil-incorporated tree-leaf biomass (prunings) both in alley cropping and sole cropping systems and to determine the extent of synchrony between mineralized N and its uptake by maize crop in the subhumid highlands of Kenya. The biomass selected for this purpose were from calliandra and leucaena. The rationale for these species is explained in Chapter 3.

Materials and Methods

The experiment was conducted at the Embu Regional Research Centre, Eastern Province, Kenya. The details of the experimental site, layout and treatments, cropping history, lopping of hedges, incorporation of biomass into the soil and other aspects of experiment management are reported in Chapter 3. The study was conducted during the long (LR) and short (SR) rainy seasons of 1995 (hereafter referred to as season 1 and 2 respectively).

Nitrogen Mineralization - Sampling and Analysis

A modification of the field incubation method for estimating *in situ* nitrogen mineralization as recommended by the Tropical Soil Biology and Fertility programme (Anderson

and Ingram 1993) was followed for this study. Six pieces of pvc tubes (30 cm long with an internal diameter of 5 cm) were randomly inserted into the soil in each plot the same day maize was planted. The tubes were driven into the soil about 25 cm (to prevent root in-growth), leaving 5 cm of the tubes projecting above the soil surface. Three of the six tubes were removed immediately and the soil in them bulked to form a sample which was analyzed to determine the initial mineral-N (NH_4^+ and NO_3^-) concentration in the soil at $time_0$ (t_0). The remaining three tubes were covered with polyethylene paper to protect the cores from leaching effects by rain. These were removed two weeks later and likewise analyzed for mineral-N concentration (t_1). Net mineralization was calculated as the difference in mineral-N between the two time points (t_1 - t_0). A similar process was repeated for all the other sampling dates, i.e., 2, 4, 7, 10, 15, and 20 weeks after maize planting. For each sampling time, net mineralization was always calculated as the difference in mineral-N between that time of determination and the one preceding it.

At each sampling, the bulked soil samples from the respective plots were packed into polyethylene bags, kept in a refrigerator (4°C) and transported immediately in cooler boxes filled with ice to the laboratory for analysis. On arrival at the laboratory, the samples were again refrigerated before extraction with 2 N KCl. The extracts

were frozen in a freezer awaiting NH_4^+ and NO_3^- analysis. To avoid contamination, NH_4^+ was analyzed first followed by NO_3^- as outlined in ICRAF laboratory manual (1995). Care was exercised to ensure that the samples were kept cold between field sampling and extraction in the lab, and that the total procedure took no more than five days to complete.

Crop N Uptake and N Recovery - Sampling and Analysis

Destructive random maize sampling was done at 4, 7, 10, 15, and 20 (harvest) WAP to determine N concentration in the plant tissue. Sampling was done outside of the net plots. To minimize gap effects, care was exercised to ensure that two consecutive plants were not removed. Dry weights (mass) of the harvested plants were determined to assist in assessing N uptake by maize at different stages of crop growth. Except at seedling stage (4 WAP), maize leaves were always separated from the stem and analyzed separately. At harvest, the cob was separated from the grain and stover and the three components analyzed separately. The samples were cleaned with water (where necessary) and oven dried at 65°C to constant weight (usually 48 hours) after which they were ground to first pass through a 2 mm and finally through a 0.5 mm sieve. The resulting powder was then kept in plastic air tight bottles and stored in a cool dry place awaiting chemical analysis. Nitrogen concentration in the samples was analyzed following the methods outlined in the ICRAF

Laboratory Manual (1995). Apparent N recovery by maize crop was calculated as follows:

$$\% N_{REC} = \frac{N \text{ uptake}_{(treatment)} - N \text{ uptake}_{(control)}}{\text{Total N applied}} * 100$$

where, N uptake $_{(treatment)}$ and N uptake $_{(control)}$ are the total N (kg/ha) in the treatment and control plots respectively.

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using SAS (1988) program. Means were separated by Tukey's procedure at the $P < 0.05$ level of significance.

Results

Nitrogen Mineralization

There were no significant trends in N mineralization with distance from the tree hedges to the center of the alley. The amounts of NH_4^+-N and NO_3^--N obtained after soil analysis at each sampling period were summed to give the total N mineralized (NH_4^+-N and NO_3^--N were converted to elemental N before summing) at a given sampling date. The bulk of inorganic N found in the soil at all the sampling periods was in the form of NO_3^--N, with NH_4^+-N contributing less than 10% of the mineralized N (data not shown).

Mineral-N content in the 0 to 20 cm soil depth ranged from 15 to 41 kg/ha and 14 to 66 kg/ha in seasons 1 and 2,

respectively, at the beginning of each season (0 WAP) (Table 4.1). The amount increased as the season progressed, peaking approximately 4 WAP in all the treatments in both seasons and declined sharply between 4 WAP and 10 WAP, after which it leveled off until harvest. Treatments where prunings were applied mineralized greater amounts of N, whereas the alley-cropped, prunings removed, and the absolute control treatments had lower amounts of mineralized N.

Cumulative mineralized N over the 20-week period under various treatments ranged from 114 to 270 kg N/ha for season 1, and 126 to 364 kg N/ha for season 2 (Figures 4.1 and 4.2). The general pattern observed across the two seasons for cumulative N mineralization was as follows: prunings applied + fertilizer treatments ≥ *ex situ* pruning applied treatments ≥ alley-cropped prunings applied treatments > fertilizer applied treatment ≥ alley-cropped prunings removed treatments = absolute control.

Nitrogen Uptake and Recovery by Maize

Nitrogen uptake by maize reached its peak during the 7 WAP and 10 WAP sampling dates in both seasons, and declined progressively thereafter until harvest (Table 4.2). Just as in the case with soil N mineralization, N uptake by maize was highest in the treatments that received prunings and lowest in the alley-cropped prunings removed treatments.

Table 4.1. Amounts of N mineralized in the 0 to 20 cm soil depth at different sampling dates during the two growing seasons of 1995 at Embu, Kenya.

		Season 1 - LR 95 (weeks)							Season 2 - SR 95 (weeks)						
Trt	AC/PI/ NF†	0‡	2	4	7	10	15	20	0	2	4	7	10	15	20
		---------- kg N/ha ----------							---------- kg N/ha ----------						
1	C/C/-	33 b	39 b	61 ab	33 a	23 b	20 a	18 ab	27 de	57 bc	69 a	30 c	19 bc	21 ab	30 b
2	L/L/-	40 a	42 b	64 ab	31 a	30 a	23 a	23 a	33 cd	63 b	49 b	40 b	23 ab	23 ab	28 b
3	C/-/-	16 d	21 c	30 c	13 c	16 bc	13 c	14 b	14 f	34 d	27 c	19 d	11 c	12 bc	9 d
4	L/-/-	16 d	22 c	32 c	15 c	17 bc	15 ab	18 ab	19 ef	39 cd	28 c	24 cd	14 c	12 bc	21 bc
5	-/C/-	27 bc	43 b	51 b	24 b	22 b	19 ab	18 ab	45 bc	107 a	76 a	25 cd	17 bc	26 ab	36 bc
6	-/L/-	41 a	41 b	56 b	36 a	21 b	22 a	19 ab	41 bc	66 b	49 b	26 cd	23 ab	29 a	32 b
7	-/C/25	37 a	67 a	77 a	23 b	23 b	21 a	23 a	57 b	92 a	51 b	56 a	26 a	35 a	47 a
8	-/L/25	32 b	42 b	66 ab	25 b	22 b	19 ab	18 ab	66 a	94 a	70 a	53 a	23 ab	26 ab	26 bc
9	-/-/50	22 c	19 c	30 c	21 b	12 c	11 c	18 ab	35 cd	52 bc	24 c	17 d	14 bc	10 c	28 b
10	-/-/-	15 d	20 c	32 c	14 c	11 c	11 c	11 bc	23 ef	44 c	22 c	16 d	22 ab	8 c	13 cd

Means followed by the same letter within a column are not significantly different at $P < 0.05$.
†AC - alley crop tree species (C = calliandra, L = leucaena)
PI - type of pruning incorporated (C = calliandra, L = leucaena)
NF - nitrogen fertilizer applied (kg N/ha)
0‡ - Amount of mineral N found in the soil at maize planting
Abbreviations: Trt = treatments; LR = long rain; SR = short rain.

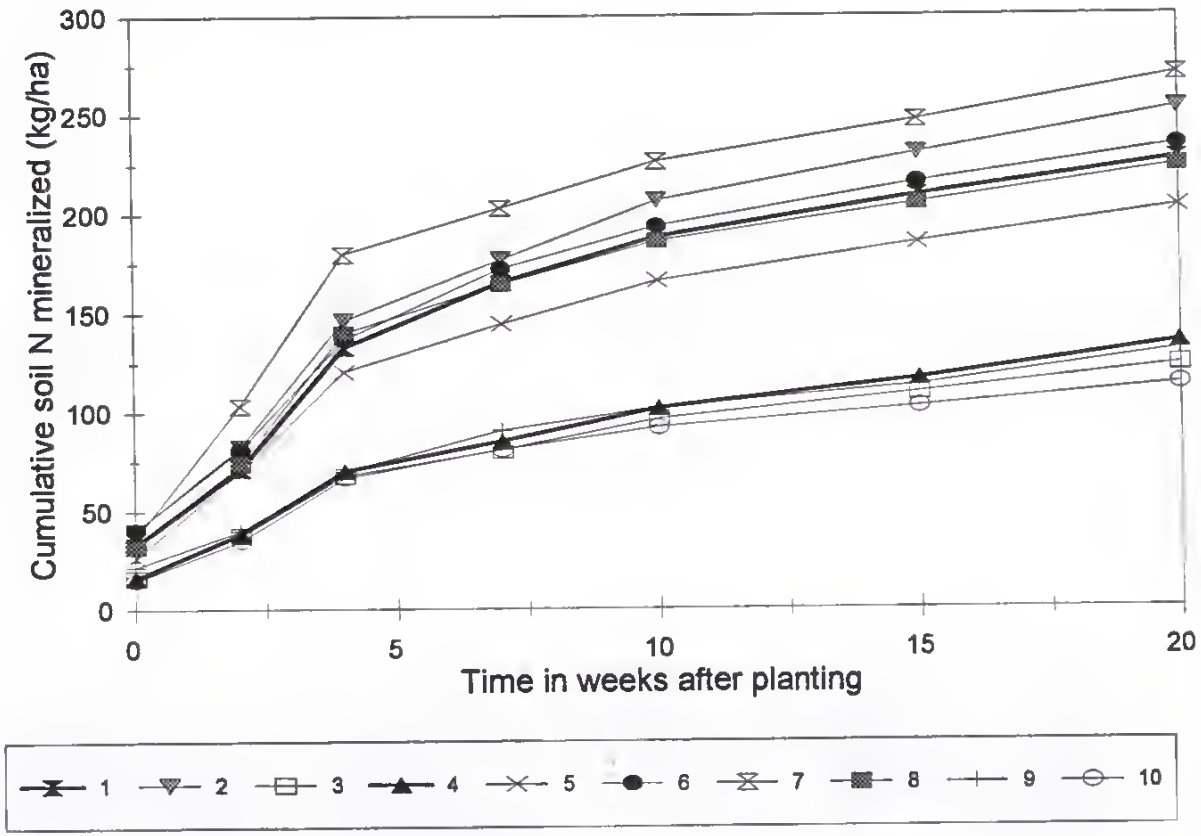

Figure 4.1. Cumulative soil N mineralized under various treatments during the long rain 1995 season at Embu, Kenya

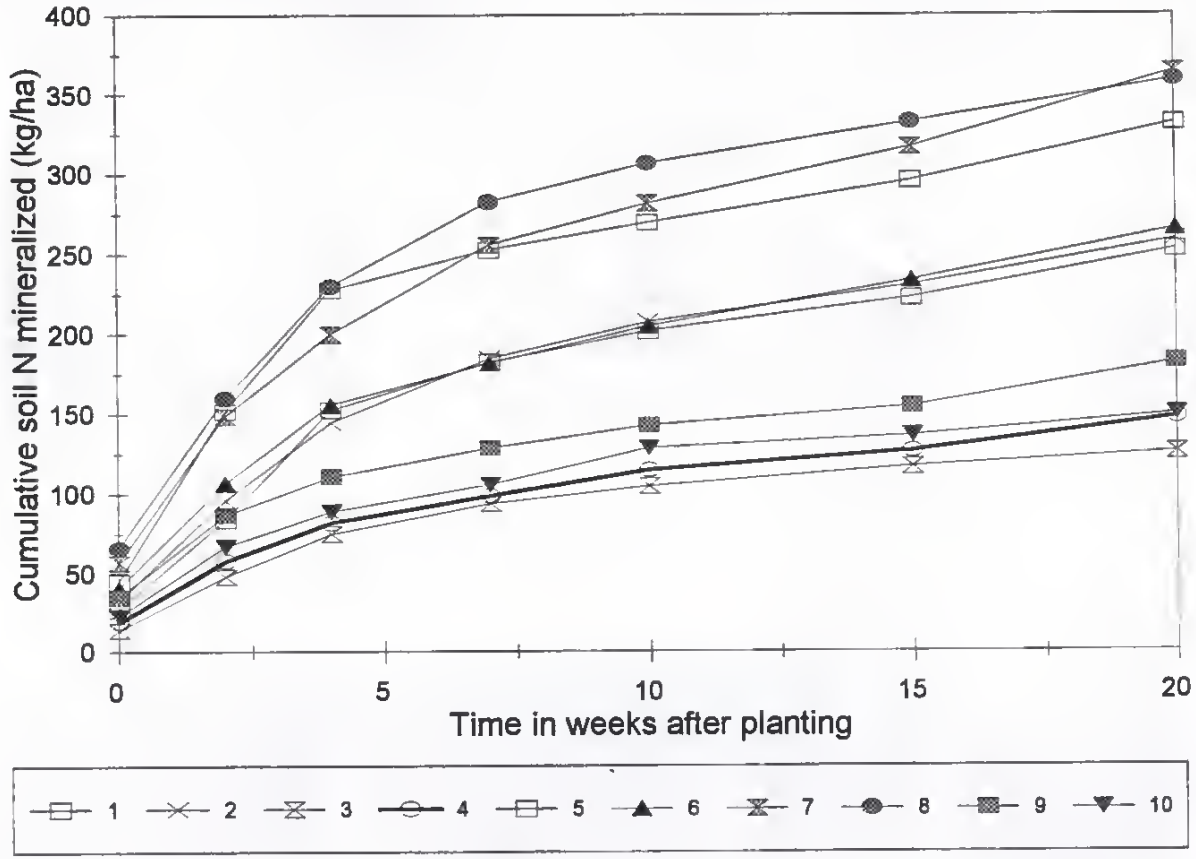

Figure 4.2. Cumulative soil N mineralized under various treatments during the short rain 1995 season at Embu, Kenya

Cumulative N uptake by maize over the 20-week study period in both seasons is presented in Figures 4.3 and 4.4. Cumulative N uptake increased rapidly up to 10 WAP after which it leveled off. At harvest (20 WAP) the cumulative N uptake ranged from 42 to 115 kg/ha for season 1 and 61 to 157 kg/ha for season 2. The pattern of N uptake by maize in the two seasons was similar to that of N mineralization, i.e., prunings applied + fertilizer treatments ≥ *ex situ* pruning applied treatments ≥ alley-cropped prunings applied treatments ≥ fertilizer applied treatment ≥ alley-cropped prunings removed treatments ≥ absolute control.

Apparent N recovery increased progressively until maize harvest during the two growing seasons of 1995 (Table 4.3). The fertilizer applied treatment gave the highest apparent N recovery in the two seasons. Calliandra alley-cropped treatment (Trt 1) recovered less N (starting 10 WAP and 15 WAP in seasons 1 and 2) compared to the control resulting in negative N recovery in both seasons.

Synchrony Between Soil-Mineralized N and Uptake by Maize

Table 4.4 presents the results of the differences (excess or deficit) between N mineralized and N taken up by maize at different sampling dates during the two growing seasons. There was substantial amount of excess N (ranging from 15 to 73 and 14 to 107 kg N/ha/sampling date in the two

Table 4.2. Nitrogen taken up by maize at different sampling dates in the two growing seasons of 1995 at Embu, Kenya.

		Season 1 - LR 95 (weeks)					Season 2 - SR 95 (weeks)				
Trt	AC/PI/NF†	4	7	10	15	20	4	7	10	15	20
		kg N/ha					kg N/ha				
1	C/C/-	3 a	26 c	19 c	18 a	7 ab	4 a	29 c	32 c	7 c	5 c
2	L/L/-	4 a	40 ab	39 ab	16 a	6 ab	4 a	44 b	50 ab	7 c	5 c
3	C/-/-	2 ab	16 d	15 d	5 c	4 bc	2 b	32 c	23 d	3 d	2 d
4	L/-/-	3 a	21 cd	23 c	5 c	5 bc	4 a	31 c	24 d	4 d	5 c
5	-/C/-	4 a	35 b	50 a	14 ab	5 bc	4 a	51 b	43 b	22 a	8 b
6	-/L/-	4 a	45 ab	46 a	12 b	3 c	4 a	53 ab	49 ab	12 b	8 b
7	-/C/25	4 a	41 b	48 a	14 ab	5 bc	4 a	54 ab	63 a	25 a	11 ab
8	-/L/25	4 a	55 a	41 a	12 b	5 bc	4 a	66 a	50 ab	15 b	8 b
9	-/-/50	3 a	33 bc	35 ab	15 ab	10 a	3 ab	47 b	20 d	21 a	14 a
10	-/-/-	3 a	27 c	27 b	20 a	6 ab	3 ab	26 cd	33 c	15 b	10 b

Means followed by the same letter within a column are not significantly different at $P < 0.05$.
†AC - alley crop tree species (C = calliandra, L = leucaena)
PI - type of pruning incorporated (C = calliandra, L = leucaena)
NF - nitrogen fertilizer applied (kg N/ha)
Abbreviations: Trt = treatments; LR = long rain; SR = Short rain.

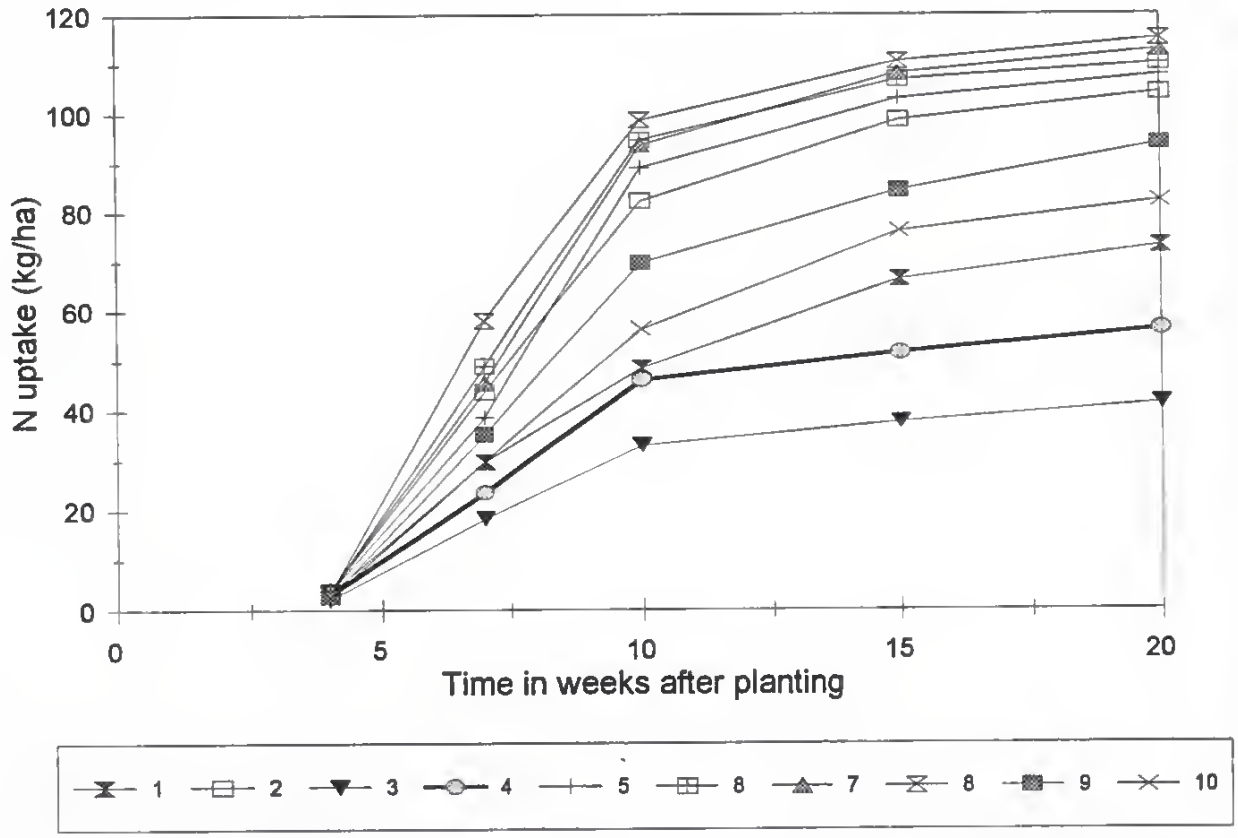

Figure 4.3. Cumualtive N taken up by maize in the various treatments during the long rain 1995 season at Embu, Kenya

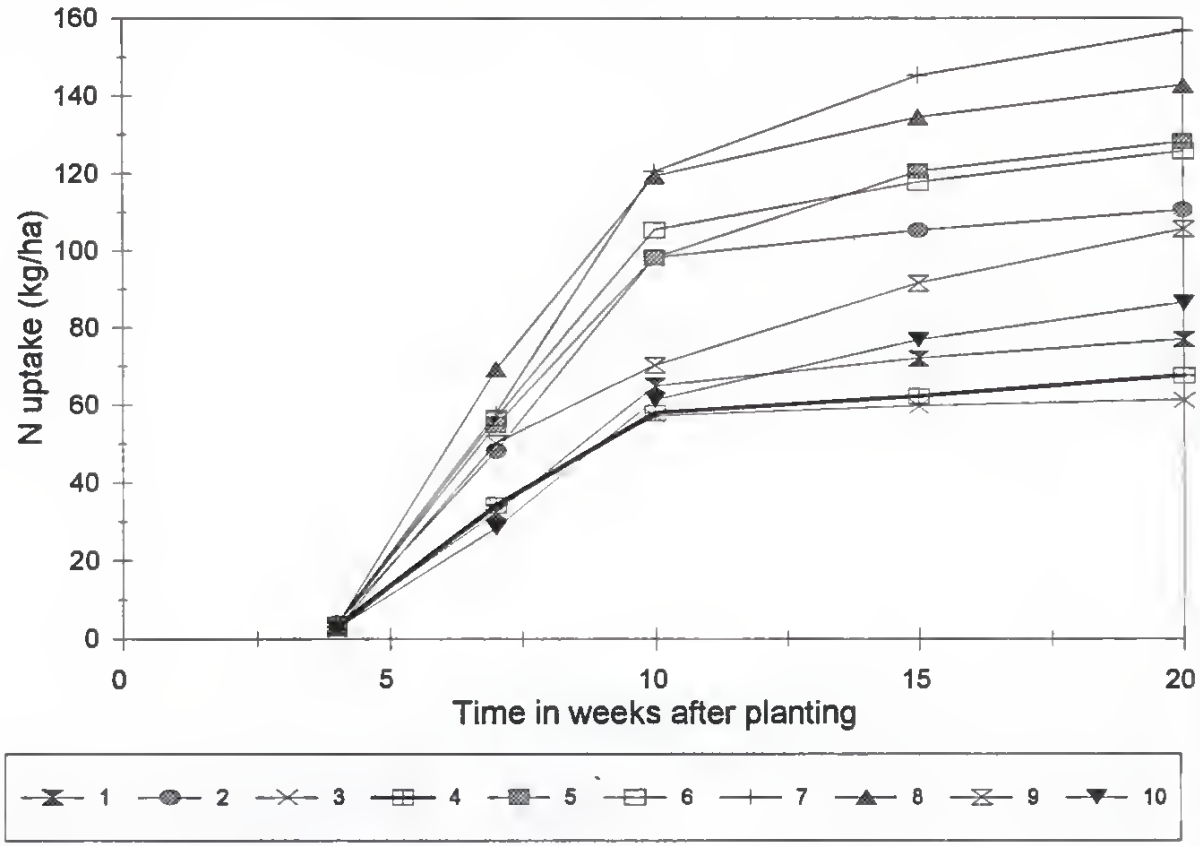

Figure 4.4. Cumulative N taken up by maize in the various treatments during the short rain 1995 season at Embu, Kenya

Table 4.3. Apparent N recovery by maize for the different treatments at Embu, Kenya during the 1995 growing seasons.

		Long rain 95 (WAP)					Short rain 95 (WAP)				
Trt	AC/PI/ NF†	4	7	10	15	20	4	7	10	15	20
		N recovery in %					N recovery in %				
1	C/C/-	1 a	0 d	-2 c	-7 d	-18 d	1 a	3 c	2 c	-6 c	-17 d
2	L/L/-	1 a	9 b	14 a	15 b	17 bc	1 a	13 ab	16 ab	18 b	19 bc
5	-/C/-	1 a	6 c	9 b	13 b	15 c	1 a	16 a	21 a	22 b	24 b
6	-/L/-	1 a	13 a	18 a	19 a	20 b	1 a	18 a	21 a	21 b	22 b
7	-/C/25	1 a	4 c	7 b	9 c	11 c	1 a	16 a	19 a	22 b	25 b
8	-/L/25	1 a	14 a	19 a	20 a	21 b	1 a	14 ab	17 ab	21 b	23 b
9	-/-/50	0 b	11 b	17 a	23 a	27 a	0 b	13 ab	18 a	30 a	38 a

Means followed by the same letter within a column are not significantly different at $P < 0.05$.
†AC - alley crop tree species (C = calliandra, L = leucaena)
PI - type of pruning incorporated (C = calliandra, L = leucaena)
NF - nitrogen fertilizer applied (kg N/ha)
Abbreviations: Trt = treatments; WAP = weeks after planting.

seasons respectively) in all the treatments in the early part of the two growing seasons (up to 4 WAP). Treatments that had prunings applied registered higher excess amounts of N than the other treatments. Nitrogen deficit started showing during the 7 WAP sampling date in both seasons. The absolute control (Trt 10) portrayed higher deficits compared to other treatments in both seasons. The prunings + fertilizer treatments (Trt 7 & 8) and the *ex situ* prunings applied treatments (Trt 5 and 6) showed minimal deficits during the two cropping seasons.

Table 4.4. Differences between N mineralized (0 to 20 cm soil depth) and N taken up by maize at different sampling dates in the 1995 growing seasons at Embu, Kenya.

		Season 1 - LR 95 (weeks)							Season 2 - SR 95 (weeks)						
Trt	AC/PI /NF†	0‡	2	4	7	10	15	20	0	2	4	7	10	15	20
		kg N/ha							kg N/ha						
1	C/C/-	33 b	39 b	58 a	-10 a	-8 b	2 c	13 ab	27 de	57 bc	65 a	-11 b	-13 b	14 a	25 b
2	L/L/-	40 a	42 b	60 a	-12 a	-9 b	7 ab	17 a	33 cd	63 b	45 b	-14 a	-27 a	16 a	23 b
3	C/-/-	16 d	21 c	28 c	-8 b	-5 c	8 ab	10 b	14 f	34 d	25 c	-13 a	-12 b	9 b	7 d
4	L/-/-	16 d	22 c	29 c	-8 b	-6 c	-10 e	13 ab	19 ef	39 cd	24 c	-7 c	-10 c	8 b	16 c
5	-/C/-	27 bc	43 b	47 b	-7 b	-8 b	5 ab	13 ab	45 bc	107 a	72 a	-6 c	-6 d	14 a	28 b
6	-/L/-	41 a	41 b	50 b	-9 b	-5 c	10 a	16 ab	41 bc	66 b	45 b	-7 c	-6 d	17 a	24 b
7	-/C/25	37 a	67 a	73 a	-8 b	-5 c	7 ab	18 a	57 b	92 a	47 b	2 d	-7 d	10 b	36 a
8	-/L/25	32 b	42 b	62 a	-3 c	-9 b	7 ab	13 ab	66 a	94 a	66 a	-3 a	-7 d	11 ab	18 c
9	-/-/50	22 c	19 c	27 c	-12 a	-5 c	-4 d	8 ab	35 cd	52 bc	21 c	-3 d	-6 d	-7 c	14 c
10	-/-/-	15 d	20 c	29 c	-13 a	-16 a	-9 c	5 bc	23 ef	44 c	19 c	-10 b	-11 b	-11 d	3 d

Means followed by the same letter within a column are not significantly different at $P < 0.05$.
†AC - alley crop tree species (C = calliandra, L = leucaena)
PI - type of pruning incorporated (C = calliandra, L = leucaena)
NF - nitrogen fertilizer applied (kg N/ha)
0‡ - Amount of mineral N found in the soil at maize planting
Abbreviations: Trt = treatments; LR = long rain; SR = short rain.

Discussion

Mineral-N present in excess of plant demand is susceptible to loss. Improved synchrony (matching release of nutrients in forms available to crops from decomposing prunings to the crop's growth and demands (Swift 1987)) implies that there is less excess mineral nutrients in the soil minimizing the opportunity for loss (Myers et al. 1994). There was excess mineral-N in the soil up to about 4 WAP, with treatments that had prunings incorporated showing greater amounts. It was observed in Chapter 5 that leucaena and calliandra soil-incorporated prunings released about 80% and 60% of N respectively after the first 4 weeks of incorporation. The relatively high N release from the prunings of these tree species helped to boost the mineral-N found in the soil in the treatments that received prunings.

In the conditions under which this study was conducted, maize grows rapidly from 4 to 10 WAP (silking/grain-filling-stage). This also is the phase where maize has the highest demand for N (Karlen et al. 1988), as exemplified by the sharp decline in the level of available mineral-N in the soil in all the treatments between 4 and 10 WAP (Table 4.1). Mafongoya and Nair (1997) reported that a large accumulation of available N in the soil before the peak period of N uptake by maize is needed to achieve synchrony between N supply from prunings and N demand by the maize crop. The question here is what is the optimal time span between the

accumulated mineral-N and the peak demand by maize to ensure minimal N loss from the system. The answer is not an easy one for it will depend on many factors, especially climatic and soil conditions. High quality prunings such as those of leucaena which release over 50% of their N two weeks after incorporation into the soil, might be releasing the N too early resulting in asynchrony between N release and critical demand by maize (Rubaduka et al. 1993; Myers et al. 1994; Mafongoya et al 1997b;c). Such available N in the soil is subject to leaching, volatilization, denitrification, and immobilization. However, despite rapid N release, incorporating high quality prunings close to planting has been shown to give superior yields as opposed to applying them too late (> 4 WAP) after planting (Kang and Mulongoy 1992; Mafongoya and Nair 1997). Indeed, Mafongoya and Nair (1997) observed that calliandra and leucaena prunings applied to an alfisol in semiarid Zimbabwe at planting gave the highest maize grain yield and N uptake, though with leucaena, prunings applied at 2 WAP and 4 WAP produced yields that did not differ significantly from the yields of those applied at planting.

The increase of mineralized N in the soil up to 4 WAP was not exclusively observed in the treatments that received prunings only, but also in all the other treatments including the control. As noted earlier, the amount of available mineral-N in the soil was substantial at the

beginning of each season, and this seemed to increase in all the treatments (with the highest increase in the prunings incorporated treatments) with the onset of rains (it is worthwhile noting that the soils of the study site had ≈ 2% C). This phenomenon in the tropical soils is commonly referred to as "nitrogen flash" or the "Birch effect" (Birch 1958). The loss especially to leaching of the increased amount of mineral-N in the soil increases as the rainfall increases (Myers et al. 1994). This loss will be more pronounced early in the season (before the crop develops extensive rooting system) if rainfall is too much. Rainfall data (Table 3.1) indicated that rainfall received during the two seasons was higher than the long term average for the area and that most of it was received during the early part of the growing season. Some N was likely lost through leaching (leaching in this study was not assessed because of logistical difficulties). Results using ^{15}N-labeled prunings that were soil-incorporated in the same treatments used in this study (Chapter 5) indicated that 20% to 30% of the labeled N could not be accounted for. A part of this amount could be assumed to have been lost through leaching. Nitrate-N, which is the principal form of the mineral-N found in these soils, is easily leachable compared to NH_4^+-N (Tisdale et al. 1993). Though N loses through denitrification were assumed to be minimal because soils were well aerated, this process cannot be totally ignored.

Firestone (1982) and Groffman et al. (1988) reported that denitrification is facilitated by the presence of nitrate in the soil and the absence of oxygen at soil microsites where decomposition is taking place. Frequent heavy storms in the region may create temporary waterlogged microsites devoid of oxygen. Nitrogen loses through volatilization were negligible since prunings were incorporated into the soil whose pH (5.5) was not high enough to facilitate this process (Myers et al. 1994).

This study shows that there were no differences between calliandra and leucaena soil-applied prunings in terms of soil N mineralization. Treatments applied with both tree biomass with and without fertilizer gave the highest mineralized N. They also came close to meeting the crop N demand at the most critical period of N requirement. The fate of the substantial amount of excess mineral-N observed in all the treatments early in the season before the crop developed extensive rooting system merits further investigations. Also, further research is needed to quantify the amount of N lost through leaching.

CHAPTER 5
NITROGEN RECOVERY BY ALLEY-CROPPED MAIZE AND TREES FROM ^{15}N-LABELED TREE BIOMASS

Introduction

Incorporation of tree-leaf biomass (prunings) into the soil is a well known agricultural practice for enhancing soil fertility and sustaining crop production (Fu et al. 1987). The practice is more prevalent in the tropics where high costs and lack of inorganic fertilizers limit their use by most small farmers (Kang 1988; FAO 1989). Though application of tree biomass to the soil has been shown to improve soil chemical and physical properties and also to sustain and increase crop yield (Kang et al. 1990; Mulongoy and Akobundu 1992), N contribution from the biomass to the associated crop has been low, representing a N recovery rate of less than 30% in most cases (Mulongoy and Meersh 1988; Xu et al 1993; Giller and Cadisch 1995; Palm 1995). The low N recovery rate from tree biomass is probably due to lack of synchronization between N demand by the crop and that released by the biomass, or N loses through volatilization, immobilization and leaching (as discussed in Chapter 4). It is also possible that decomposition of biomass may lead to retention of N in organic forms in the soil-N organic pool

that are resistant to rapid mineralization (Haggar et al. 1993). Very few studies have been conducted to quantify the fate of applied N in biomass and especially the transfer of N from biomass to crops.

The objective of this study was to trace the path of N in ^{15}N-labeled calliandra and leucaena biomass when incorporated into crop field in an alley cropping situation. Amounts of ^{15}N assimilated by maize crop and by calliandra and leucaena tree hedges at different dates were assessed.

Materials and Methods

Experimental Site

The study was conducted in the same experimental site reported in Chapter 3.

Labeling of Calliandra and Leucaena Prunings with ^{15}N

In March 1995, Calliandra and leucaena tree species, (which had been planted in 1992) in the external boundaries surrounding the experimental site, were labeled using 10 atom % ^{15}N double-labeled fertilizer in the form of ammonium-^{15}N nitrate-^{15}N that was obtained from Isotope Services, Inc., USA. One hundred plants of each tree species were selected and pruned clean of all the leaves to a height of 50 cm. Approximately one gram of the enriched fertilizer was dissolved in about one liter of water before applying around

the base of each tree using a watering can. Subsequent watering was done to move the fertilizer into the soil. The trees were supplied with the enriched fertilizer in a similar manner at four-week intervals during four consecutive months. In early August, one month after the last application, the trees were pruned back to 50 cm height (initial biomass). The harvested prunings were sun dried to constant weight. The leafy biomass was separated from the small branches and twigs, and then stored in gunny bags for use in the short rain season of 1995 (SR 95). Random subsamples of the biomass from both species were taken for the determination of the level of the ^{15}N enrichment. Reference samples were also harvested from calliandra and leucaena trees that had not been labeled.

After the initial pruning in August, the trees were allowed to sprout and to grow for another five months (no ^{15}N fertilizer was added) after which they were pruned and the resulting biomass treated as above (residual biomass). This biomass was used in the long rain season of 1996 (LR 96).

Experimental Treatments

The experimental treatments for the ^{15}N study were demarcated on the existing experimental treatments as outlined in Chapter 3. Treatments 1 and 2 (calliandra and leucaena alley-cropped with maize) were selected for this study because we also wanted to monitor nutrient uptake by

maize and tree hedges. Microplots measuring 2 x 9 m were demarcated in the middle of the existing plots that measured 9 x 10 m (Figure 3.1). Ten trees (five on either side of the hedge) were selected for this purpose. The ^{15}N labeled biomass was incorporated in these microplots at the rate of 1 kg/m^2. Prunings from the trees that were included in the study (and hence received labeled biomass) were, together with the other prunings coming from the other trees in the same plot, applied on the other portions of the plot that did not receive ^{15}N biomass. Litter bags containing 50 g of the labeled biomass were also incorporated into the soil plow layer in the microplots. The details on the incorporation of biomass are described in Chapter 3.

Sampling and Sample Handling

Maize was planted after the labeled biomass was incorporated into the soil. Subsequently, maize plants were sampled at 4, 7, 10, 15, and 20 (harvest) weeks after planting (WAP). Young leaves from calliandra and leucaena tree hedges that had received the labeled biomass were also sampled during the same intervals. Except at seedling stage (4 WAP), maize leaves were always separated from the stem and analyzed separately. At harvest (20 WAP), the cob was separated from the grain and stover. Maize roots and soil were also sampled at this stage. At every sampling date, reference samples (from unlabeled trees) were also taken

along side those from enriched plots. Samples were cleaned with water and oven dried at 65°C to constant weight.

Litter bags containing labeled biomass were removed from the soil at the time maize plants were sampled. The contents in the bags were cleaned with water, oven dried, and dry weights recorded.

All the samples were ground through a 0.5 mm sieve mill. The resulting powder was thoroughly mixed, packed in polyethylene bags and stored under dry conditions and shipped to the University of Florida (USA) for analysis.

Analysis of ^{15}N

Samples were analyzed for ^{15}N using a Carbon Nitrogen Analyzer 1500 (Carlo Erba) coupled with an isotope ratio mass spectrometer (VG 602E). Recovery of the applied N was calculated following Westerman et al. (1972) equation:

$$\% \text{ N recovered} = 100\ p\ (c-b)/f\ (a-b)$$

where,

p = total N uptake in plant
f = amount of fertilizer N applied
a = atom % ^{15}N concentration in fertilizer
b = atom % ^{15}N concentration in soil
c = atom % ^{15}N concentration in plant

Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using SAS (1988). Means were separated by LSD procedure and declared different at $P < 0.05$ level of significance.

Results

Enriched ^{15}N Tree-Biomass

Tree leafy-biomass harvested after the trees had received continuous application of enriched ^{15}N fertilizer for four months (SR 95 - initial) revealed that leucaena prunings had a significantly higher concentration of the labeled N than calliandra prunings (Table 5.1). The concentration of the unlabeled (normal) N was also significantly higher in leucaena than in calliandra's biomass. The naturally occurring ^{15}N from the reference samples in the biomass of both species was identical though slightly higher than the reported level of 0.3663% that occurs freely in the atmosphere (Bremer 1965). Analysis of the second generation biomass (subsequent pruning after the initial; LR 96 - residual) revealed no differences in concentrations between the labeled N in the biomass of both species, although calliandra had significantly higher concentration of unlabeled N. The amount of ^{15}N that appeared in the residual biomass was substantial and was close to the amounts initially recovered by the trees during the first pruning, indicating that substantial amount of the ^{15}N applied initially in the fertilizer had been left either in the tree stems and roots or in the soil N pool.

Table 5.1. Concentration of ^{15}N in labeled calliandra and leucaena biomass before incorporation into the soil at Embu, Kenya.

Season	Biomass	Normal N	Enriched ^{15}N	Total N	Reference ^{15}N
		---------- concentration in g/100g ----------			
SR 95	Calliandra	4.0 b	0.6085 b	4.6 a	0.3692 a
(Initial)	Leucaena	4.2 a	0.7280 a	4.9 b	0.3687 a
LR 96	Calliandra	4.1 a	0.5357 a	4.6 a	0.3680 a
(Residual)	Leucaena	3.7 b	0.5228 a	4.2 b	0.3682 a

Means followed by a different letter within a column in a particular season are significantly different at $P < 0.05$.
Abbreviations: SR = short rain; LR = long rain.

Concentration and Recovery of ^{15}N by Maize and Tree Hedges Four Weeks after Planting

The concentration of labeled N in maize was higher in treatments that received leucaena enriched biomass compared to those treated with calliandra prunings in both seasons, although the differences were only significant during the SR 95 season (Table 5.2). Recovery of ^{15}N ranged from 0.5% to 0.8% by maize and 0.3% to 0.8% by trees in the two seasons respectively. It was only the LR 96 recovery values by trees that were significantly different (Table 5.2).

Table 5.2. Concentration, uptake and recovery of labeled and unlabeled nitrogen by maize and tree hedges four weeks after planting maize during the two cropping seasons at Embu, Kenya.

		N conc (g/100g) (maize seedlings)		N conc (g/100g) (in tree leaves)		Labeled N in plants (kg/ha)		Total N uptake (kg/ha)		Recovery of labeled N (%)	
Season	Trt†	Unlabeled	Labeled	Unlabeled	Labeled	Maize	Trees	Maize	Trees	Maize	Trees
SR 95	Call	4.8 a	0.5011 b	4.4 a	0.3835 a	2.6 a	1.6 a	4.6 a	26.7 a	0.7 a	0.4 a
	Leuc	4.8 a	0.5729 a	4.8 a	0.3838 a	2.8 a	1.0 a	5.1 a	25.0 a	0.8 a	0.3 a
LR 96	Call	3.0 a	0.4671 a	4.2 a	0.3808 a	1.9 a	2.9 a	3.2 a	24.9 a	0.5 a	0.8 a
	Leuc	3.1 a	0.4761 a	4.4 a	0.3874 a	2.1 a	1.9 b	3.0 a	22.9 a	0.6 a	0.5 b

Means followed by the same letter within a column in a particular season are not significantly different at $P < 0.05$.
†Trt = treatments with enriched ^{15}N calliandra and leucaena prunings.
Abbreviations: Trt = treatments; SR = short rain; LR = long rain; Call = calliandra; Leuc = leucaena.

Concentration and Recovery of ^{15}N by Maize and Tree Hedges at Later Stages of Crop Growth

Concentrations of the labeled N in both maize and tree tissues increased to highest levels during the 7 to 10 WAP and declined progressively thereafter until crop harvest (20 WAP) during SR 95 season (Table 5.3). No such trend was observed during the LR 96 season. On the other hand, unlabeled N had its highest concentration 4 WAP in both seasons (both in maize and tree leaves) which decreased progressively as the seasons advanced (Tables 5.2, 5.3, and 5.5). Maize in the treatments that received labeled leucaena biomass had a higher concentration of ^{15}N in both the leaves and stems compared to that where labeled calliandra biomass was applied at 7, 10, and 15 WAP in SR 95 season (Table 5.3). The differences were all significant except at 10 WAP. A similar but non significant trend was observed during the LR 96 season.

Higher significant N uptake was observed in maize treated with labeled leucaena biomass compared to that treated with calliandra biomass (except 7 WAP - SR 95). On the other hand, calliandra tree hedges had a higher N uptake compared to leucaena tree hedges in each of the three sampling dates during the two growing seasons (Table 5.3).

Application of labeled leucaena biomass resulted in higher levels of labeled N in maize plants (kg/ha) leading to higher recovery of ^{15}N in leucaena prunings-applied

Table 5.3. Concentration and uptake of labeled and unlabeled nitrogen by maize and tree hedges 7, 10, and 15 weeks after planting maize during the two cropping seasons at Embu, Kenya.

			N conc (g/100g) (maize leaves)		N conc (g/100g) (maize stems)		N conc (g/100g) (tree bedge leaves)		Total N uptake (kg/ha)	
Season	WAP	Trt†	Unlab	Labeled	Unlab	Labeled	Unlab	Labeled	Maize	Trees
SR 95	7	Call	3.6 a	0.5121 b	3.1 a	0.4999 b	4.7 a	0.3938 a	44.9 a	56.3 a
		Leuc	3.2 b	0.5842 a	3.0 a	0.5838 a	4.9 a	0.4016 a	45.7 a	51.2 b
	10	Call	2.4 a	0.5257 a	1.2 a	0.5080 a	4.1 a	0.3917 a	75.4 b	78.2 a
		Leuc	2.2 a	0.5147 a	1.3 a	0.5083 a	3.6 a	0.4003 a	108.2 a	59.4 b
	15	Call	1.1 a	0.4543 b	0.5 a	0.4537 b	3.7 a	0.3903 a	78.0 b	87.9 a
		Leuc	1.2 a	0.4897 a	0.6 a	0.5053 a	3.1 a	0.4003 a	113.5 a	64.3 b
LR 96	7	Call	2.9 a	0.4620 a	2.0 a	0.4696 a	4.3 a	0.3874 a	48.3 b	51.2 a
		Leuc	3.0 a	0.4739 a	2.1 a	0.4701 a	4.5 a	0.3872 a	58.9 a	46.7 b
	10	Call	2.8 a	0.4861 a	1.4 a	0.4914 a	3.7 a	0.3881 a	65.1 b	67.1 a
		Leuc	2.6 a	0.4663 a	1.5 a	0.4714 a	3.7 a	0.3859 a	87.5 a	57.3 b
	15	Call	1.8 a	0.4708 a	0.7 a	0.4597 a	3.7 a	0.3806 a	72.2 b	87.9 a
		Leuc	2.0 a	0.4806 a	0.8 a	0.4737 a	3.5 a	0.3874 a	98.7 a	73.2 b

Means followed by the same letter within a column at a particular sampling time are not significantly different at $P < 0.05$.
†Trt = treatments with enriched ^{15}N calliandra (call) and leucaena (leuc) prunings.
Abbreviations: Trt = treatments; WAP = weeks after planting (maize); SR = short rain; LR = long rain; Call = calliandra; Leuc = leucaena; Unlab = unlabeled (normal) N.

Table 5.4. Concentration and recovery of ^{15}N by maize and tree hedges 7, 10, and 15 weeks after planting maize during the two cropping seasons at Embu, Kenya.

			Labeled N in plants (kg/ha)			Recovery of labeled N (%)			
Season	WAP	Trt†	Maize leaves	Maize stems	Trees	Maize leaves	Maize stems	Total (maize)	Trees (leaves)
SR 95	7	Call	30.4 a	8.7 b	5.8 a	5.2 b	0.9 b	6.1 a	1.5 a
		Leuc	32.5 a	12.2 a	4.7 a	7.4 a	3.3 a	10.7 a	1.3 a
	10	Call	36.8 b	12.4 b	7.1 a	5.7 b	1.8 b	7.5 b	1.8 a
		Leuc	44.5 a	14.9 a	5.0 b	8.3 a	3.5 a	11.8 a	1.5 a
	15	Call	37.3 b	12.9 b	7.8 a	6.1 b	2.4 b	8.5 b	2.2 a
		Leuc	45.6 a	15.2 a	5.8 b	8.9 a	3.7 a	12.6 a	1.7 a
LR 96	7	Call	19.7 b	7.0 b	5.9 a	3.7 a	1.1 a	4.8 a	1.6 a
		Leuc	29.6 a	10.1 a	5.7 a	4.3 a	2.1 a	6.4 a	1.5 a
	10	Call	25.4 b	9.2 b	8.1 a	5.3 a	1.9 a	7.2 a	2.1 a
		Leuc	33.7 a	12.3 a	6.5 b	6.1 a	2.4 a	8.5 a	1.9 a
	15	Call	28.2 b	10.2 b	9.1 a	5.5 b	2.1 a	7.6 b	2.6 a
		Leuc	35.4 a	12.1 a	6.9 b	7.3 a	2.8 a	10.1 a	2.0 b

Means followed by the same letter within a column at a particular sampling time are not significantly different at $P < 0.05$.
†Trt = treatments with enriched ^{15}N calliandra (call) and leucaena (leuc) prunings.
Abbreviations: Trt = treatments; WAP = weeks after planting (maize); SR = short rain; LR = long rain; Call = calliandra; Leuc = leucaena.

treatments compared to treatments that received calliandra prunings (Table 5.4). Calliandra tree hedges, however, had higher levels of the labeled N and higher recovery than leucaena hedges though the differences were only significant at 15 WAP in LR 96 season.

Concentration and Recovery of ^{15}N by Maize and Tree Hedges at Maize Harvest

The concentration of the labeled N in maize grain, cob, stover, and roots were significantly higher in the treatments that received labeled leucaena biomass compared to those that received labeled calliandra biomass in the SR 95 season (Table 5.5). Similar differences were not obvious during the LR 96 season.

Maize crop in the leucaena-biomass-applied treatments took up a significantly higher amount of N (kg/ha) than in the calliandra-biomass-applied treatments in both seasons (Table 5.5), leading to a higher proportion of the labeled N in the former compared to the latter treatments (Table 5.6). However, an opposite scenario was observed with the tree hedges where calliandra hedges had a significantly higher N uptake and higher level of labeled N in their tissue (Tables 5.5 and 5.6).

Recovery of ^{15}N in different parts of the maize crop varied, the grain accounting for the highest, followed by the stover (Table 5.6). Total ^{15}N recovered by maize was

Table 5.5. Nitrogen concentration and uptake by maize and tree hedges at maize harvest during the two cropping seasons at Embu, Kenya.

		N conc (g/100g) in maize grain		N conc (g/100g) in maize cob		N conc (g/100g) in maize stover		N conc (g/100g) in maize roots		N conc (g/100g) in tree leaves		Total N uptake (kg/ha)	
Sson	Trt†	Unlab	Lab	Unlab	Lab	Unlab	Lab	Unlab	Lab	Unlab	Lab	Maize	Trees
SR	Call	1.4 a	0.485 b	0.4 a	0.465 b	0.4 a	0.477 b	0.7 a	0.519 b	4.7 a	0.394 a	79.0 b	99.3 a
(95)	Leuc	1.4 a	0.515 a	0.5 a	0.473 a	0.5 a	0.498 a	0.8 a	0.530 a	4.9 a	0.402 a	116.0 a	73.0 b
LR	Call	1.6 a	0.462 a	0.5 a	0.449 a	0.9 a	0.439 a	0.9 a	0.441 a	3.4 a	0.384 a	75.7 h	103.5 a
(96)	Leuc	1.7 a	0.477 a	0.5 a	0.448 a	1.0 a	0.440 a	1.0 a	0.444 a	2.9 a	0.383 a	112.6 a	74.9 b

Means followed by the same letter within a column in a particular season are not significantly different at $P < 0.05$.
†Trt = treatments with enriched ^{15}N calliandra (call) and leucaena (leuc) prunings.
Abbreviations: Sson = season; Trt = treatments; SR = short rain; LR = long rain; Lab = labeled (^{15}N); Unlab = unlabeled (normal N).

Table 5.6. Concentration and recovery of ^{15}N by maize and tree hedges at maize harvest during the two cropping seasons at Embu, Kenya.

		Labeled N in plants (kg/ha)						Recovery of labeled N (%)							
Season	Trt†	Maize					Trees	Maize					Trees	Soil	unacc-ounted
		Grain	Cob	Stover	Roots	Total		Grain	Cob	Stover	Roots	Total			
SR 95	Call	24.0b	1.4a	17.3b	3.3b	46b	8.2a	5.3a	0.3a	2.9b	0.8b	9.3b	2.7b	69.3a	19.6b
	Leuc	32.7a	1.8a	21.8 a	4.7a	61a	6.4a	6.5a	0.3a	5.0a	1.4a	13.0a	2.1a	55.0b	29.7a
LR 96	Call	21.2b	1.1a	16.1a	2.8a	41b	9.9a	4.7a	0.5a	2.4a	0.6b	8.2b	3.2a	66.7a	21.9b
	Leuc	28.4a	1.2a	19.3a	3.4a	52a	7.1b	5.5a	0.4a	3.7a	1.2a	10.8a	2.5b	61.4b	25.3a

Means followed by the same letter within a column are not significantly different at $P < 0.05$.
†Trt = treatments with enriched ^{15}N calliandra (call) and leucaena (leuc) prunings.
Abbreviations: Trt = treatments; SR = short rain; LR = long rain; Call = calliandra; Leuc = leucaena.

higher in the treatments that received labeled leucaena biomass. Calliandra tree hedges recovered significantly higher amount of the labeled N compared to leucaena hedges though the recoveries were low (2.7% and 3.2% for calliandra and 2.1% and 2.5% for leucaena for the two seasons respectively). A major part of the N applied to the soil through the labeled prunings was left in the soil pool at the end of the two growing seasons: 55% and 61% for leucaena and 69% and 67% for calliandra for SR 95 and LR 96; and that approximately 20% to 22% and 25% to 30% could not be accounted for in the case of calliandra- and leucaena-prunings-applied treatments, respectively.

Decomposition and ^{15}N Release

Leucaena biomass decomposed and released ^{15}N at a significantly faster rate than calliandra biomass during all the sampling dates except at 20 WAP when the differences were not significant (Figures 5.1 and 5.2).

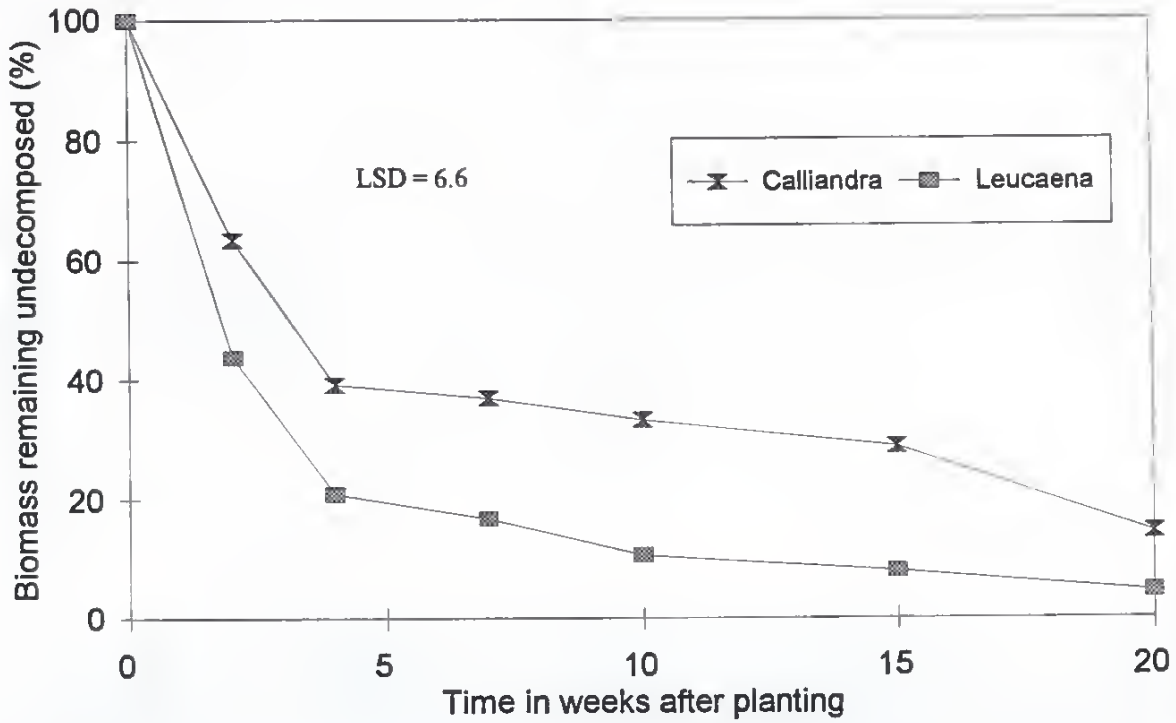

Figure 5.1. Decomposition patterns of calliandra and leucaena N-15 labeled biomass during the SR 1995season at Embu , Kenya

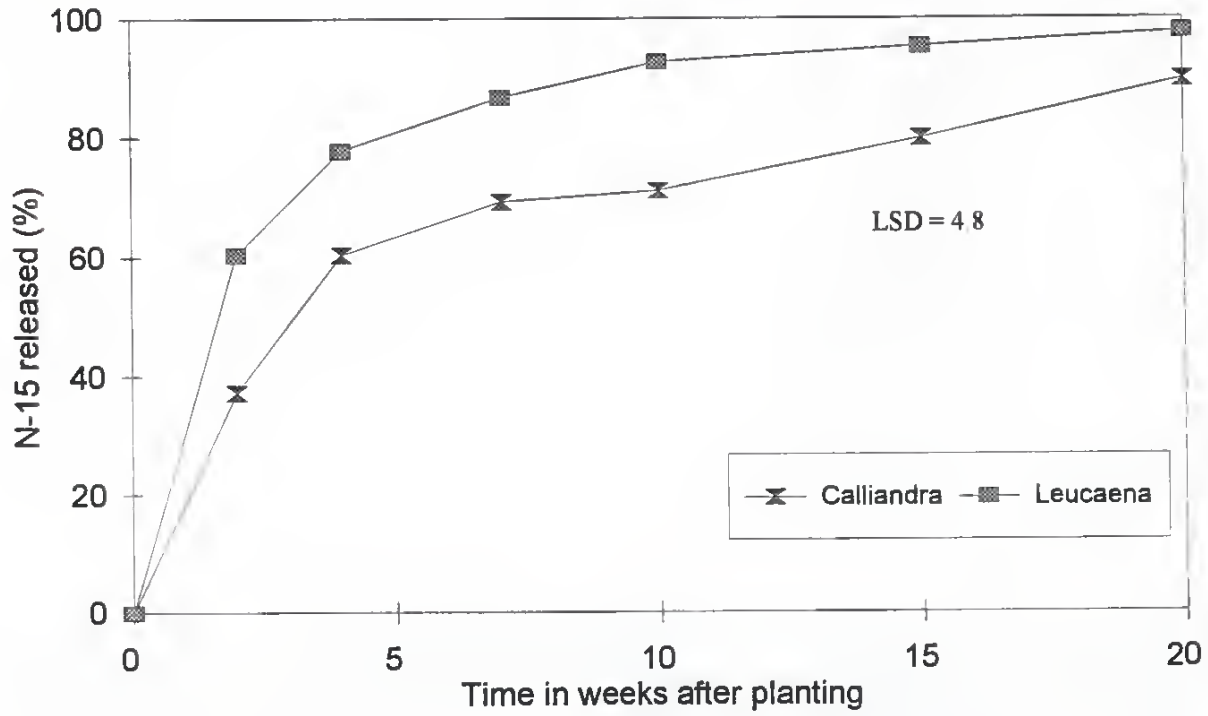

Figure 5. 2. Total N-15 released by decomposing calliandra and leucaena biomass during the SR 1995 season at Embu, Kenya

Discussion

Total N uptake and ^{15}N recovery by the maize crop increased rapidly in the four to ten WAP and then leveled off between 10 and 20 WAP. Maize has the highest demand for N starting from four WAP to around tasseling/silking stage (10 WAP), which is also the period coinciding with its most rapid growth phase (Karlen et al. 1988; Hagger et al. 1993). This period is, however, determined by climate, soil type, and the maize variety. By tasseling/silking stage, the crop will have taken up more than 90% of its N requirements from the soil. In addition, continuous retranslocation of N occurs from older parts to newer tissues as the plant develops. Approximately 60% of the unlabeled N that appeared in the maize leaves and stalks 7 WAP seems to have been retranslocated at 15 WAP (Table 5.3). The amount retranslocated increased further by harvest (20 WAP). Similar trends were observed with the labeled N, although the amounts retranslocated were not as high as with the unlabeled N. The results agree with those of Weiland (1989) who reported as much as 60% of N retranslocation from the leaves to the grain.

Treatments that received labeled leucaena biomass produced maize that had consistently higher ^{15}N concentration and higher N uptake than calliandra labeled biomass-applied treatments especially during the SR 95 growing season. The

reason for this could be that, labeled leucaena biomass applied initially (SR 95) had a higher concentration of ^{15}N compared to calliandra biomass. Secondly, leucaena biomass decomposed and released N faster than calliandra biomass. Thirdly, as discussed in Chapter 3, calliandra tree hedges compared to leucaena tree hedges seemed to be too competitive and depressed maize yields. This explains why maize N uptake was lower in the calliandra alley cropped treatments compared to leucaena alley cropped treatments.

Recovery of ^{15}N by maize crop increased as the season progressed. Recovery figures reported here, though low, are consistent with the 5% to 20% recovery range reported in the literature (Ladd et al. 1981; Haggar et al 1993; Jansen 1994). Most of the N from the biomass was left in the soil N pool as was shown by the high figures of the labeled N in the soil pool after the end of the season. Calliandra biomass, with a relatively lower decomposition and N release rate than leucaena, had more of the labeled N left in soil and less of it unaccounted for compared with leucaena biomass. Other researchers, working with labeled N reported as high as 80% of N applied in the biomass as having been left in the soil after the first season's crop (Ladd et al 1981; Ng Kee Kwong et al. 1987; Haggar et al. 1993; Becker et. al 1994a). It is generally assumed that the large N fraction remaining in the soil at the end of the season would decompose later and have some residual effects on the

second season's crop. This, however, did not seem to be the case since the recovery figures of the second season's crop were not higher than those of the first season except for the tree hedges. This observation agrees with the findings of many other researchers who reported little or no residual effects on succeeding crops (Singh et al. 1991; Ladha et al. 1992). The low level of residual effects on succeeding crops could be because organic substrates left after the more labile organic portions decompose form part of the soil humus containing components that decompose and release nutrients slowly (Becker et al. 1994b).

Recovery of ^{15}N by tree hedges was relatively low, but comparatively more in calliandra than in leucaena hedges. This again may be explained by the more aggressive rooting system of calliandra compared to leucaena trees (as explained in Chapter 3). No other published results are available to compare and contrast with these data. More such studies need to be conducted to determine how much of the nutrients applied in the tree-leaf biomass are taken up by the tree hedges.

Some of the relatively large amounts of labeled N that were unaccounted for may have been left in the stem and root portions of the tree hedges (since N in the tree hedges was only determined in the tree leaves). The rest of the N may have been lost, principally through leaching, as discussed in Chapter 4.

The lower amount of the ^{15}N that was unaccounted for in the treatments that received labeled calliandra biomass compared to those that received leucaena biomass was due to the fact that calliandra biomass decomposed and released N at a much slower rate than leucaena biomass, possibly due to calliandra's high polyphenolic concentrations which are known to bind with N lowering the rate of decomposition and N release (Chesson 1997).

This study demonstrates that application of N-rich biomass in alley cropping systems contributes more to the long term build up of soil N than in meeting the current season's crop N requirements.

CHAPTER 6
PREDICTING THE DECOMPOSITION PATTERNS OF TREE BIOMASS IN HIGHLAND MICROREGIONS OF KENYA

Introduction

In many agroforestry systems, leaf biomass (litter or leafy prunings) of multipurpose trees (MPT) is added as a source of N and other nutrients to crops (Nair 1993). Decomposition and mineralization (nutrient release) of the biomass are the key processes by which nutrients locked up in plant parts eventually become available to crops. The processes are regulated by a host of variables including physical and chemical properties (quality) of litter, climate, soil properties and decomposer communities consisting of microorganisms and soil invertebrates (Meentemeyer and Berg 1986; Upadhyay and Singh 1989). Understanding the extent of influence or control of these variables over biomass decay and nutrient release is an important first step to better managing organic inputs that are applied in agroforestry and other related land-use systems (Palm 1995; Mafongoya et al. 1997c).

The influence of litter quality on decomposition and nutrient release has recently been reviewed by Palm (1995). Initial concentrations of nitrogen (N), lignin (LG),

polyphenol (PP) and ratios such as C:N, LG:N, (LG+PP):N, and PP:N in the biomass, are some of the chemical factors that have been shown to influence decomposition rates (Frankenberger and Abdelmagid 1985; Tian et al. 1993; Palm and Sanchez 1991; Constantinides and Fownes 1994; Mafongoya and Nair 1997). However, there is no unanimity of views as to which of the chemical indices and ratios are the best predictors of decomposition and nutrient release; in addition other factors, such as microclimate and decomposer communities, species differences, contents and proportions of chemical constituents in the plant materials, and the analytical methods employed, are also important (Palm 1995; Quemada and Carbrera 1995).

Reports on the role of differing environments and their interaction with litter chemical indices in decomposition and nutrient release are few. Meentemeyer (1978) showed that climatic factors such as actual evapotranspiration (AET) were a better predictor of decay rate than were litter quality factors (e.g., lignin) when considering different climatic regions (subpolar to warm temperate). Other abiotic factors influencing the rate of decomposition included temperature and rainfall (Upadhyay and Singh 1989; Upadhyay et al. 1989; Sandhu et al. 1990). These studies dealt mostly with forest litter decay and were often localized on single sites. Studies on how litter quality and abiotic environment affect decomposition on multilocational sites in

agroforestry systems are unavailable. The objective of this study was to develop a regression model that describes the influence of plant chemical qualities, climate, and soil characteristics on decomposition patterns across different microregions (subhumid to semiarid) in the tropical highlands of Kenya where agroforestry is being practiced.

Materials and Methods

Characterization of Microregions

The study was conducted in the central highlands of Kenya, during season 1 and 2 (the long (LR) and short (SR) rainy seasons) of 1995. Four contrasting environments (microregions) were selected in accordance with Jaetzold and Schmidt's (1983) agroecological zonation of the area: microregions 1 to 4 corresponds to Jaetzold and Schmidt's classification of upper midlands 1 to 4 (UM1 to UM4). The geographic and climatic details of the four microregions (henceforth referred to as Reg1, Reg2, Reg3, and Reg4) are presented in Table 6.1. The average daily soil temperatures (recorded using soil thermometers for the 0 to 15 cm top soil layer) and total rainfall (from daily readings) in the different microregions during the experimental period are presented in Table 6.2. The soil properties of the sites are shown in Table 6.3.

Table 6.1. Geographic and climatic[1] descriptors of the four microregion sites in the highlands of Kenya.

Region	Altitude (m)	Average air temp (°C)			Average total Rainfall (mm)		
		Max	Min	Mean	LR	SR	Total
1	1700	23.5	12.6	18.0	1050	700	1750
2	1440	25.0	14.1	19.5	800	600	1400
3	1320	27.6	16.9	21.2	540	460	1000
4	1596	31.0	13.3	19.0	400	350	750

[1]climatic data represent ≥ 10 years.
Abbreviations: LR = long rain season; SR = short rain season.
Source: Jaetzold and Schmidt (1983).

Experimental Procedures

Biomass of three tree species were chosen for the study: calliandra (*Calliandra calothyrsus* Meïssner), cordia (*Cordia africana* Lam.) and grevillea (*Grevillea robusta* Cunn. ex. R. Br.). The species are common in the study region. Calliandra (originated from tropical America) was introduced in the study area in the early 1980s as a source of fodder and for soil fertility enrichment. Cordia is indigenous and is found frequently scattered in crop lands; farmers allow it to grow on farms because of its perceived ability to improve soil fertility. Grevillea was introduced from Australia in the 1920s. It is now the most common tree found on farms throughout Kenyan highlands; it is used for fuelwood and as a building material. Its prunings are spread on coffee farms or used as bedding in cowsheds.

Table 6.2. Average soil temperature (0 to 15 cm depth) and total rainfall in the four microregions during the two study seasons in the highlands of Kenya.

		Season 1 (LR 95)						Season 2 (SR 95)					
	Week	0-2	2-4	4-7	7-10	10-15	15-20	0-2	2-4	4-7	7-10	10-15	15-20
Temp	Reg1	21.0	19.2	18.6	17.9	16.3	13.0	12.2	11.5	10.8	11.1	11.9	13.0
(C)	Reg2	23.8	22.1	20.1	19.3	17.1	16.0	18.8	18.0	17.8	16.7	15.5	17.0
	Reg3	27.9	27.3	25.0	24.4	20.9	21.1	25.4	25.1	25.9	23.5	23.0	25.0
	Reg4	Data Not Recorded						24.6	23.0	22.5	21.7	23.6	25.0
Rain	Reg1	80	179	450	64	32	118	336	292	92	119	101	3
(mm)	Reg2	80	140	251	30	9	39	145	119	73	67	68	9
	Reg3	93	167	162	34	5	14	111	61	49	82	42	13
	Reg4	Data Not Recorded						99	26	19	69	12	29

Season 1, 24 March-11 August 1995; Season 2, 19 October 1995-5 March 1996.
Abbreviations: LR = long rain season; SR = short rain season.

Table 6.3. Soil properties for the decomposition sites in the different microregions in the highlands of Kenya.

Region	Site	Soil Type	pH (water)	C (g/100g)	N (g/100g)	P (g/100g)
1	Kavutiri	Orthoxic Palehumult	4.8 b	2.41 a	0.41 a	0.11 a
2	Embu	Typic Palehumult	5.8 a	1.95 ab	0.23 b	0.09 a
3	Murinduko	Typic Palehumult	5.6 a	1.44 bc	0.16 bc	0.08 a
4	Machakos	Kandic Rhodustalfs	6.1 a	1.17 c	0.09 d	0.09 a

Values followed by the same letter within a column are not significantly different from each other at $P < 0.05$.

Leafy biomass used in each microregion was obtained from mature trees found in that region or near the respective study sites. Leaves and twigs (no more than 2 mm in diameter) were collected and sun dried to constant weight after which samples of 50 g each were transferred to litter bags of 2 mm mesh-size. The bags were then buried in the ground at a depth of 0 to 15 cm (plow-layer). The experiment was installed as a randomized block design, replicated three times within each region. One bag containing residues of each species was randomly removed from each block (in each region) after 2, 4, 7, 10, 15, and 20 weeks. The contents of the bag were carefully cleaned free of soil and oven dried at 65°C (for about 48 h) to constant weight (Anderson and Ingram 1993). The dry weight of the litter remaining undecomposed was recorded.

Decomposition rate constants (k) were estimated using the Wieder and Lang (1982) first order exponential equation:

$$L_R/L_I = e^{-k \cdot t}$$

Where: L_R = the litter weight remaining at a given time, L_I = the initial litter weight at time zero, t = the time interval of sampling L_R expressed in years, and k = the rate constant (decomposition rate per year). The fraction of the material remaining (L_R/L_I) declined with time. The k values were estimated using a nonlinear module in SAS (1988).

Nitrogen released (RLS) over time was calculated following the formula by Giashuddin et al. (1993):

% N RLS = 100 - % of original N content remaining (N_o)

where,

$$N_o = \frac{(\%\ N \text{ at time } t)}{(\%\ N \text{ at time } 0)} * \%\text{ of original wt remaining}$$

The data were analyzed as a three-way factorial study with region, species, and time (expressed in years) as fixed effects. Tree biomass samples were analyzed for initial contents of N, C, lignin and polyphenols by methods outlined by Anderson and Ingram (1993). The plant and soil analyses data were subjected to ANOVA using SAS. Means were separated by Tukey mean separation procedure at $P < 0.05$. Regression and correlation analyses were also performed relating the rate of decomposition to three groups of factors: biomass quality (N, C, lignin, and polyphenol contents, and the ratios between some of them), climate

(soil temperature and rainfall), and soil conditions (pH, total N, organic N, and total P). Statistical models were then developed relating the rate of decomposition to the three groups of factors. The contribution of each group toward the rate of decomposition was estimated by partitioning its percent contribution to the overall variability (R^2) obtained in each model.

Results

Reg1 was the coolest site and received the highest amount of rainfall, whereas Reg3 and Reg4 had the highest temperatures and received the lowest amounts of rainfall (Table 6.2). In season 1, the temperatures in all regions were highest at initiation of the experiment (0 to 2 weeks) and decreased progressively as the season advanced. The amount of rain received in this season increased from the start of the study reaching a maximum during weeks 4 to 7 and declined thereafter. Soil temperatures recorded in season 2 did not vary greatly across the season (within each region); however, the highest amount of rainfall was recorded during the first two weeks of the experiment. Reg1 had lowest soil pH and highest soil carbon and nitrogen contents compared to all other sites (Table 6.3).

The MPT biomass used in this study showed some variation in initial chemical composition (Table 6.4). Calliandra obtained from the different regions had the

Table 6.4. Initial chemical properties and ratios of different tree biomass incorporated in different regions in the tropical highlands of Kenya.

Region	Spp	N	C	LG	PP	C:N	LG:N	PP:N	(LG+PP):N
		---------- g/100g ----------							
1	Call	2.9 a	45 b	12.4 b	11.0 a	15.9 b	4.4 c	3.9 a	8.2 b
	Cord	2.8 a	46 b	28.1 a	4.3 b	16.4 b	10.1 b	1.5 b	11.7 b
	Grev	1.4 b	47 a	23.8 a	4.6 b	32.7 a	16.5 a	3.2 ab	19.8 a
2 & 4	Call	3.6 a	45 b	12.4 c	11.2 a	12.6 c	3.5 c	3.1 ab	6.6 c
	Cord	2.7 b	46 b	31.3 a	2.6 c	16.9 b	11.5 b	1.0 b	12.4 b
	Grev	1.3 c	48 a	23.7 a	6.1 b	39.4 a	19.7 a	5.1 a	24.8 a
3	Call	2.3 a	45 b	13.4 b	15.4 a	19.3 b	6.0 c	6.6 a	12.6 b
	Cord	2.2 a	45 b	26.0 a	6.0 b	20.4 b	12.0 b	2.8 b	14.8 b
	Grev	1.3 b	48 a	26.2 a	6.5 b	38.1 a	21.0 a	5.2 a	26.8 a

Values followed by different letters in a column within each region are different from each other at $P < 0.05$.
Abbreviations: LG = lignin; PP = polyphenol; Call = calliandra; Cord = cordia, Grev = grevillea.

highest concentration of N (though not significantly different from that of cordia) and polyphenols (PP) and the lowest concentration of lignin (LG). Nitrogen, C, and the C:N ratio for calliandra and cordia biomass were similar. Grevillea biomass had the lowest concentration of N and the highest concentration of C and, therefore, the highest C:N ratio. Lignin and polyphenol concentrations for grevillea were similar to those of cordia; however, its LG:N, PP:N and (LG+PP):N ratios were significantly higher than those from the biomass of the other two species in all the regions.

Decomposition patterns of the biomass were affected by both the region (environment) and the type of species (region-by-species interaction). Figure 6.1 shows an example of the decomposition patterns obtained during the two seasons of experimentation. Decomposition rates were in the order calliandra ≥ cordia > grevillea (Table 6.5).

Patterns of cumulative mineralized N (N released) of the biomass of the three species was influenced by region and species. An example of the different patterns over the 20-week study period is shown in Figure 6.2. Calliandra and cordia tree-biomass showed a pattern of rapid N release whereas grevillea showed an initial net N immobilization followed by a slow release. The highest amounts of cumulative mineralized N were given by calliandra biomass, though in some regions they were not significantly different from those of cordia. Grevillea biomass released the lowest

Table 6.5. Decomposition rate constants (k) and coefficients of determination (R^2) values for the different tree-biomass as influenced by different microregions in the tropical highlands of Kenya.

	Season 1 (LR 95)						Season 2 (SR 95)							
	Reg1		Reg2		Reg3		Reg1		Reg2		Reg3		Reg4	
Spp	k	R^2	k	R^2	k	R^2	k	R^2	k	R^2	k	R^2	k	R^2
Call	4.4 a	0.68	5.9 a	0.84	6.2 a	0.90	7.4 a	0.66	6.9 a	0.86	5.9 a	0.86	8.2 a	0.88
Cord	3.7 a	0.65	5.3 a	0.79	5.6 a	0.89	5.7 a	0.71	5.4 a	0.79	3.2 b	0.89	4.9 b	0.93
Grev	2.8 b	0.75	3.5 b	0.72	3.7 b	0.82	2.1 b	0.54	3.2 b	0.82	2.7 c	0.78	3.1 c	0.92

Values followed by the same letter within a column are not significantly different from each other at $P < 0.05$.
k values are k/yr.
Abbreviations: Call = calliandra; Cord = cordia; Grev = grevillea; LR = long rain; SR = short rain.

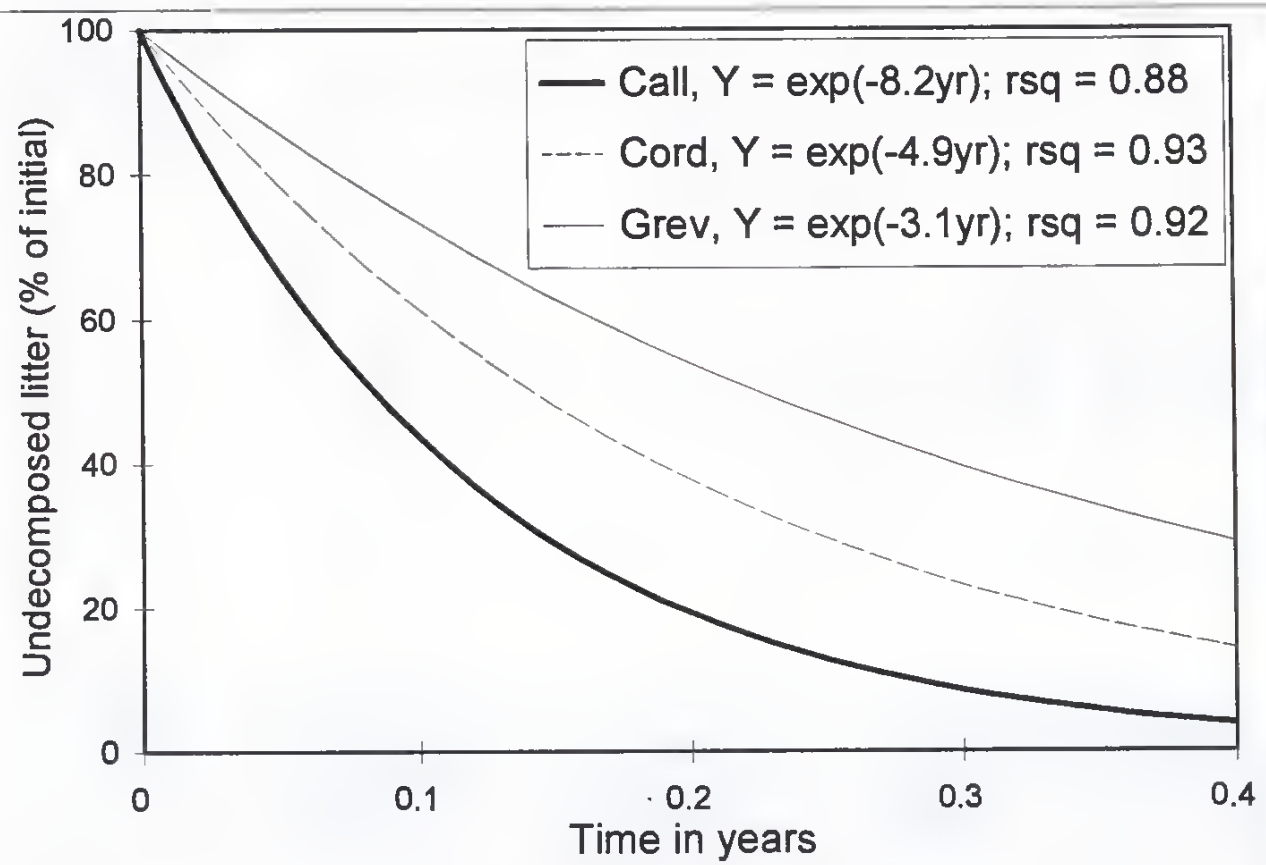

Figure 6.1. Decomposition patterns of calliandra (call), cordia (cord), and grevillea (grev) biomass for season 2 (Reg4) in the highlands of Kenya.

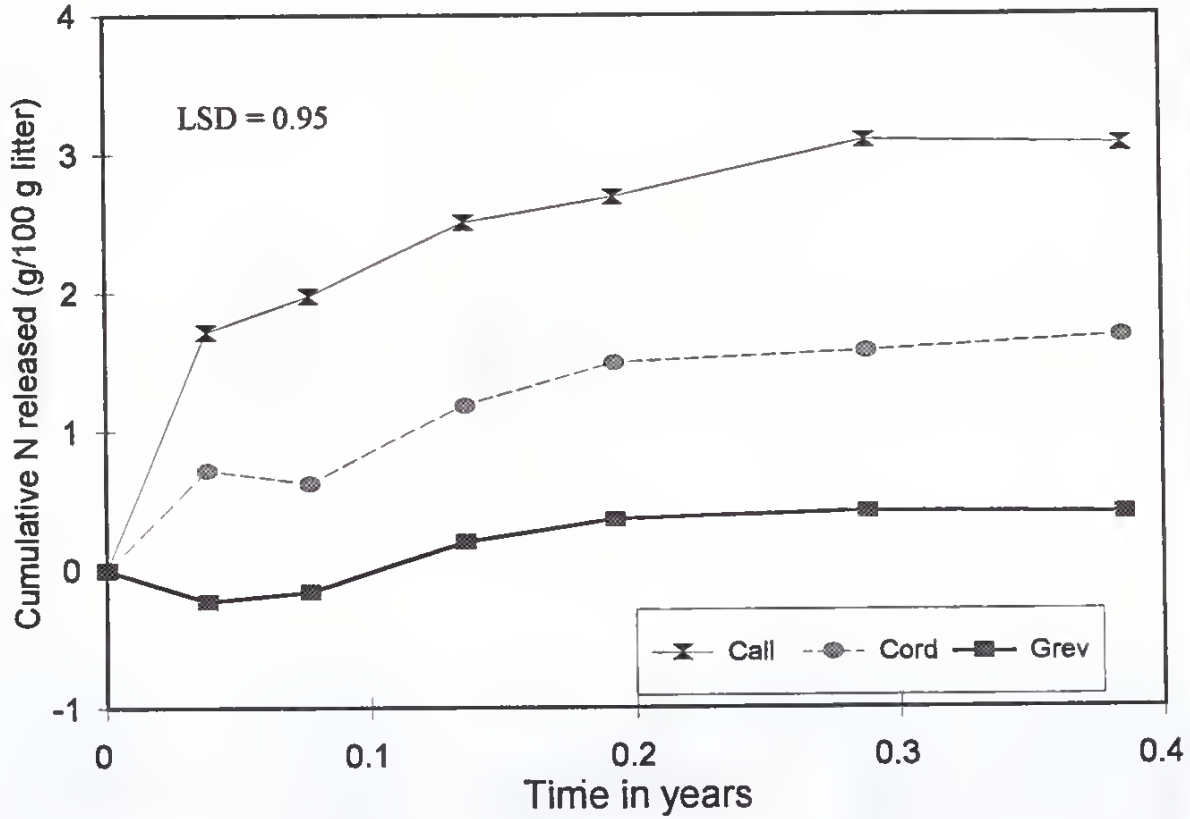

Figure 6.2. Cumulative N released over a 20-week period by calliandra (call), cordia (cord), and grevillea (grev) leafy biomass for season 1 in the different microregions of the tropical highlands of Kenya.

amounts of cumulative N in both seasons and in all the regions. The cumulative amounts of N released after 20 weeks ranged from 1.68 to 3.47 g/100g for calliandra, 0.98 to 1.78 g/100g for cordia and 0.17 to 0.44 g/100g for grevillea (Table 6.6); representing amounts of N released of 65% to 96%, 48% to 66%, and 12% to 34% of the initial N contents for calliandra, cordia, and grevillea biomass, respectively.

Correlation coefficients relating the rate of decomposition to plant, climate, and soil characteristics are shown in Table 6.7. In both seasons, rainfall, N, C:N, LG:N and (LG+PP):N, and, in addition, temperature for season 1 and lignin for season 2, were significantly correlated with the rate of decomposition.

Regression models were developed using SAS to describe decomposition pattern as a function of three groups of factors: litter quality (N, C, lignin, polyphenol, and various ratios), climate (soil temperature and rainfall), and soil characteristics (pH, total N, organic C, and total P). For each season, the best ten regression models based on adjusted R^2 were listed in a descending order. The best of the ten models (listed first in each case) for both seasons are presented in Table 6.8. In both seasons, temperature, rainfall, N, C:N, LG:N, (LG+PP):N, pH and soil total N were significant indices for predicting the rate of decomposition; in addition, LG was also important in season 2. The adjusted R^2 values were 0.88 and 0.91 for seasons 1

Table 6.6. Cumulative amount of nitrogen released over a 20-week period by tree-biomass in different microregions of the tropical highlands of Kenya.

	Total amount of N released in g/100g						
	Season 1 (LR 95)			Season 2 (SR 95)			
Spp	Reg1	Reg2	Reg3	Reg1	Reg2	Reg3	Reg4
Call	1.88 a	3.07 a	1.71 a	1.97 a	3.40 a	1.68 a	3.47 a
Cord	1.53 a	1.68 b	1.46 a	1.78 a	1.30 b	0.98 b	1.62 b
Grev	0.43 b	0.40 c	0.44 b	0.17 b	0.30 c	0.40 c	0.44 c

Values followed by the same letter within a column are not significantly different from each other at $P < 0.05$.
Abbreviations: Call = calliandra; Cord = cordia; Grev = grevillea; LR = long rain; SR = short rain.

and 2, respectively. Figure 6.3 presents the overall contribution of climatic factors, litter quality, and soil characteristics to decomposition rate in each season. Climate was the dominating factor in season 1 accounting for almost 75% of the total rate of decomposition, whereas in season 2 biomass quality was more influential accounting for 65% of the total variability.

Table 6.7. Correlation coefficients (r) relating the rate of decomposition to plant, climate, and soil factors in the highlands of Kenya in the two seasons of 1995.

Season	Temp	Rain	N	LG	PP	C	C:N	LG:N	(LG+PP):N	pH	TC	TN	TP
1 (LR)	0.45***	0.39***	-0.30**	0.22	-0.22	0.24	0.32*	0.31*	0.29*	-0.21	-0.19	-0.21	-0.22
2 (SR)	0.12	0.40**	-0.55***	0.33*	-0.27	0.32	0.50***	0.51***	0.52***	-0.04	-0.02	-0.10	-0.08

Levels of significance: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.
Abbreviations: LG = lignin; PP = polyphenol; TC = total soil organic carbon; TN = total soil nitrogen; TP = total soil phosphorus; LR = long rain season; SR = short rain season.

Table 6.8. Regression models predicting decomposition rates across different microregions in the highlands of Kenya in seasons 1 (LR 1995) and 2 (SR 1995).

Season	Model
1	$Y = Exp(yr*(-10.4 - 0.2T + 0.04R + 0.8N - 0.07C:N + 0.4(LG+PP):N + 0.2pH + 6.8TN))$; $R^2 = 0.91$
2	$Y = Exp(yr*(-2.4 + 0.03T - 0.01R + 4.4N - 0.3C:N + 4.2LG:N - 3.6(LG+PP):N + 0.2pH - 1.2TN))$; $R^2 = 0.93$

Abbreviations: Y = fraction of biomass remaining undecomposed; yr = time expressed in years; T = soil temperature (°C); N = plant nitrogen concentration (%); R = rainfall (mm); LG:N = lignin:nitrogen ratio; (LG+PP):N = (lignin + polyphenol):nitrogen ratio; pH = soil pH; TN = soil total nitrogen (%).

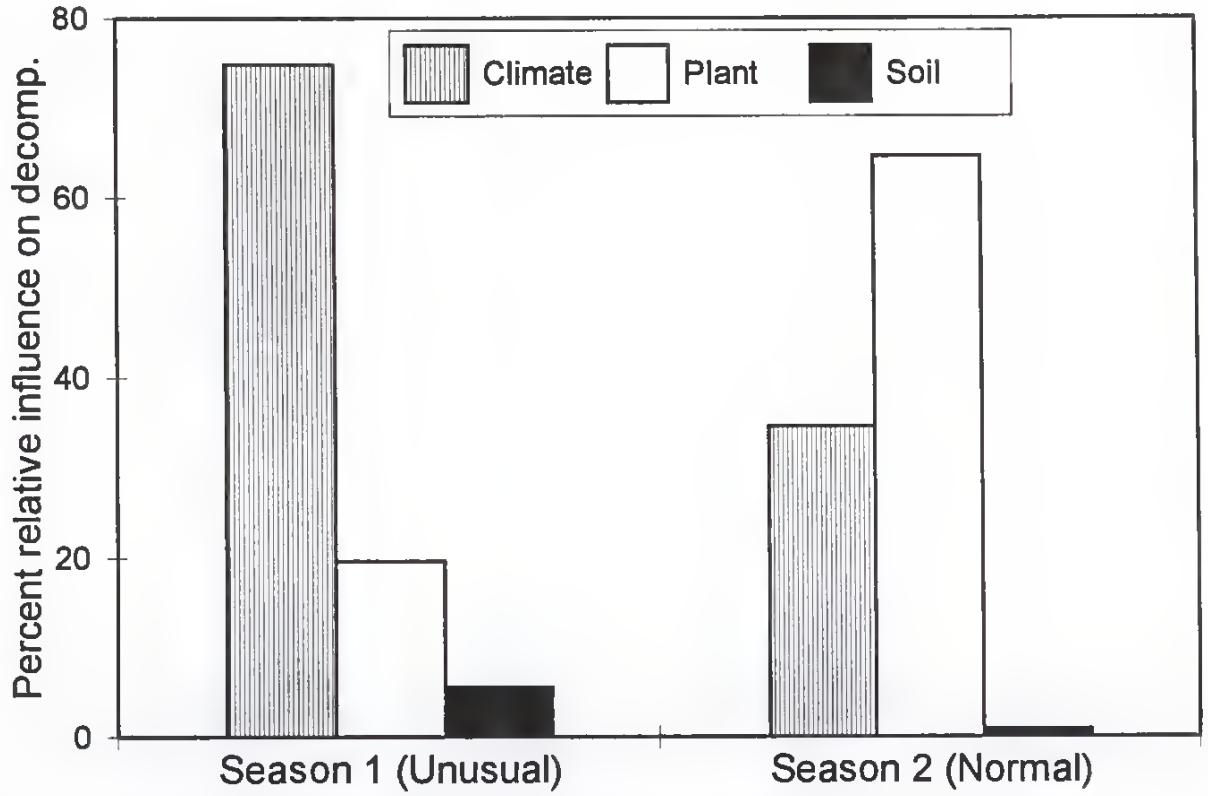

Figure 6.3. Influence of climatic, litter-quality, and soil factors on decomposition rates of tree biomass in four microregions of the tropical highlands of Kenya.

Discussion

Biomass Quality and Decomposition

The decomposition patterns of calliandra and cordia were somewhat similar and distinctly different from that of grevillea (Figure 6.1 and Table 6.5). N-release patterns were also similar to decomposition patterns; however, they could not be adequately described by simple equations due to observed variations of net release and net immobilization from one sampling period to the next. These variations did not follow any definite pattern. Among the plant indices that were shown to be effective in determining the rate of decomposition (Table 6.7), N, C, C:N, LG:N, and (LG+PP):N were best correlated with the rate of decomposition for both seasons. Past studies have indicated initial N content and C:N ratio of plant materials to be reliable predictors of decomposition and N release (Sandhu et al. 1990; Mugendi et al. 1994a; Thorup-Kristensen 1994; Quemada and Cabrera 1995; Jama and Nair 1996). In our study, the N and C:N ratio were significantly correlated with decomposition during both seasons (Table 6.7). Both calliandra and cordia biomass had high concentrations of N compared to that of grevillea (Table 6.4). The biomass from these two species showed a faster rate of decomposition whereas grevillea biomass showed an initial N immobilization in all the sites during the two seasons, and released the lowest amount of N over

the entire 20-week study period. The results of this study corroborate the reports of others that N content serves as a useful preliminary index of decomposition and N release when materials of different categories (e.g., leguminous and non-leguminous) are grouped together (Tian et al. 1992; Constantinides and Fownes 1994; Palm 1995).

Lignin had a significant positive correlation with the rate of decomposition during season 2 only. Whereas lignin content in itself was not a strong predictor of decomposition rate, lignin-derived variables (ratios) were important predictors (Table 6.7). Lignin is known to be highly resistant to microbial decomposition (Melillo et al. 1982; Chesson 1997). It may also slow down N mineralization due to lignin-bound N. The lignin concentration of cordia biomass (26% to 31%) was significantly higher than that of calliandra (12% to 13%), though both species had almost identical N concentration and C:N ratios (Table 6.4). This may partly explain why cordia biomass decomposed and mineralized at a relatively slower pace compared to calliandra. The influence of lignin on decomposition is widely reported in literature (Melillo et al. 1982; Fox et al. 1990; Palm and Sanchez 1991; Oglesby and Fownes 1992; Tian et al. 1992; Stump and Binkley 1993; Becker et al. 1994b; Chesson 1997). Lignin, however, seems to affect the rate of decomposition and N release only if the species used have relatively high levels of lignin concentration and are

structurally different (Taylor et al. 1989; Mafongoya and Nair 1997).

Polyphenol content in the plant biomass had no significant correlation with decomposition in this study. This corroborates the work of Fox et al. (1990), Becker et al. (1994b), and Handayanto et al. (1994) who found no relationship between cumulative N released and soluble polyphenol content. This, however, disagrees with the work of Palm and Sanchez (1991), Oglesby and Fownes (1992), and Tian et al. (1992). As already mentioned, the initial N content seems to be a better predictor of decomposition rate in materials that are very different in chemical composition. When materials are similar in nature (e.g., legumes), then other indices such as polyphenols may become important predictors (Constantinides and Fownes 1994; Palm 1995). Plant carbon by itself had no significant correlation with the rate of decomposition. The range of C in the biomass of the tree species was very narrow (45% to 48%) and this may explain why this constituent was not an important index in determining the rate of decomposition, however its ratio with N was significant in both seasons.

In the present study, LG:N and (LG+PP):N ratios were also observed to be significantly correlated with decomposition. These observations agree with those of others in which these ratios were found to be among the best descriptors in predicting weight losses and N release from

plant materials (Melillo et al. 1982; Fox et al. 1990; Stump and Binkley 1993; Handayanto et al. 1994; Mafongoya and Nair 1997; Mafongoya et al. 1997a).

Influence of Climate and Soil

Rainfall and soil temperature were significantly correlated with decomposition rate (Table 6.7). Total soil N and pH, though not significantly correlated with the rate of decomposition, were included in the multivariate mathematical models in Table 6.8. Literature is scarce on the combined use of climatic, plant, and soil indices in the prediction of decomposition and nutrient release, especially in agroforestry systems. In the present study, the combined effects of the three groups of factors (climate, plant-quality, and soil) on the influence of the rate of decomposition indicated that climate played a key role in regulating the rate of decomposition in season 1 (Figure 6.3) when temperature and rainfall fluctuated (Table 6.2) much more than in season 2, which was dominated by plant-quality factors. Soil factors played a minimal role in both seasons. This finding corroborates the work of Meentemeyer (1978), who indicated that climate was a more important predictor of decomposition than litter quality when dealing with multilocational sites that had differing climates. However, when dealing with a particular region that had a reasonably uniform microclimate and terrain, litter quality

indices were excellent predictors of the rate of decomposition. Other studies by Meentemeyer and Berg (1986) indicated that about 90% of a first-year litter mass loss could be explained by a simple model combining the influence of climate and nutrient concentration of the litter. Sandhu (1990) also found a significant correlation between the rate of decomposition of various portions of leucaena with moisture content and mean maximum litter temperature in the dry tropics. Similarly, Upadhyay et al. (1989) predicted monthly rainfall to be a more reliable factor regulating monthly weight loss of litter on individual sites in the Central Himalayan forests as opposed to annual temperature, actual evapotranspiration and altitude, which were better indices of annual weight loss. Vanlauwe et al. (1994) reported that the number of rainfall events gave a better correlation with the percentage dry matter loss than was the total amount of precipitation.

Regression Models

From the regression models presented in Table 5.8, it appears that most of the indicators that had a significant correlation with the rate of decomposition (Table 6.7) were also the best indices in predicting decomposition rates. After apportioning the contribution of each index to the total variability in each model, it was observed that in season 1, climatic factors were more influential in

regulating the rate of decomposition as they accounted for 75% of the total variability (Figure 6.3). The influence of temperature was especially marked during this season when there was a very clear trend of decreasing temperature as the season progressed (Table 5.2). Plant-quality factors played a major role in Season 2 accounting for 65% of the total variability. Soil factors accounted for minimal variability in the two seasons. None of the soil factors correlated significantly with the rate of decomposition.

This study indicates that the principal factors regulating the rate of decomposition in the different microregions in the Kenyan tropical highlands are climate (soil temperature and rainfall) and the quality of tree biomass (N, C:N, LG:N, and (LG+PP):N). The main difference between seasons 1 and 2 of this study was that climatic conditions (rainfall and temperature) were more "regular" and evenly distributed in season 2 (as in a normal season), than in season 1 (Table 6.2). This indicates that, during "good" seasons with average climatic conditions (as in season 2), biomass decomposition is governed predominantly by plant quality factors, whereas climatic factors (rainfall and temperature) are more important during seasons of uneven or irregular conditions. Thus, the prevailing general assumption that decomposition of plant litter in a given region is determined predominantly by plant quality factors may not necessarily be true. During seasons of erratic

climatic changes (e.g., erratic rainfall and fluctuating temperatures as is common in most semiarid tropics), climatic factors become more important than plant quality factors in determining litter decomposition rates. More research that includes other plant materials that are used in these regions as organic soil amendments by farmers is needed to improve further on the predictability of these models and the validity of the findings.

CHAPTER 7
CONCLUSIONS, SYNTHESIS, AND RECOMMENDATIONS

The overall objectives of this study were to evaluate the influence of soil-incorporated tree-leaf biomass on soil fertility and maize crop performance, and gain more understanding on the processes involved in N release from decomposing biomass. The fate of released N, in terms of its uptake by the maize crop and hedgerow trees and the balance left in the soil N pool, was investigated. The study consisted of four major parts, and each formed a major chapter (Chapters 3, 4, 5, and 6). All field measurements were repeated during cropping seasons.

Chapter 3 that reports the influence of soil-incorporated leaf prunings of calliandra and leucaena on maize yields in sole cropping and alley cropping systems shows that, in the central highlands of Kenya, the degree of success of alley cropping technology will depend a great deal on the choice of tree species and the management options employed. Though calliandra had earlier been identified as an important species capable of improving crop yields and sustaining soil fertility, it proved to be too competitive causing maize-yield reduction in alley cropping arrangements, as compared to leucaena. However, application

of calliandra leaf-biomass from the cut-and-carry system (*ex-situ* source) to the maize crop resulted in maize yields identical to those from similar application of leucaena biomass; indeed, maize yields in the two cut-and-carry systems were better than that from the application of recommended level of inorganic fertilizer. However, application of tree biomass at the quantities used in this study can not entirely substitute chemical fertilizers when maize yields at or near the maximum level are targeted.

The objectives of the investigations reported in Chapter 4 were to assess the rate of N mineralization of soil-incorporated prunings and determine if there was synchrony between the mineralized N its uptake by maize. Both N mineralization and synchrony were highest in treatments that received tree biomass with or without inorganic fertilizers and least in the absolute control treatment. However, relatively high levels of mineral-N were found in the soil early in the cropping season; more investigations are therefore necessary to get a clearer picture of synchrony between release of N from decomposing biomass and its uptake by the crop.

The fate of ^{15}N in calliandra and leucaena ^{15}N-labeled tree-leaf biomass after incorporation into the soil is reported in Chapter 5. Most of the ^{15}N applied in the leaf-tree biomass remained in the soil-N pool at the end of the current season. The results show that the benefit of the

applied biomass is more in the long term buildup of soil N rather than in meeting the N requirements of the current crop. The large N fraction remaining in the soil at the end of the season will probably decompose during a longer period and thus cause residual effects on succeeding crops.

Chapter 6 deals with development of a regression model to describe the influence of plant chemical qualities, climate, and soil characteristics on decomposition patterns across different microregions (subhumid to semiarid) in the tropical highlands of Kenya where agroforestry is being practiced. This study revealed that the prevailing general assumption that decomposition of tree biomass is determined predominantly by plant quality factors was not always true: during seasons of erratic climatic changes (e.g., fluctuating temperatures), climatic factors were more important than plant quality factors in influencing the rate of biomass decomposition. Climatic factors accounted for 75% of the total variability in the "abnormal" season whereas plant-quality factors accounted for 65% of the total variability in the more "regular" ("normal") season.

Based on the studies presented here, the following recommendations can be drawn:

1. Calliandra is not desirable for alley cropping in the subhumid tropical highlands of Kenya. Smallholder farmers should be encouraged to plant it in blocks or along the boundaries for cut-and-carry system. Due to

its fodder qualities, farmers may opt to feed it to cattle and transfer the manure to the fields, or use it directly as a green manure.

2. For best crop yields, pruning application should be supplemented with at least some amounts of inorganic fertilizer.
3. The extent of benefits derived from biomass application depends on the quantity applied: the more the better. Ways of producing higher amounts of prunings should therefore be investigated.
4. More studies are needed to monitor the relatively large amount of the unaccounted for soil N (20% to 30%) that was assumed to have been lost and the large amount of mineral-N found in the soil early in the season.
5. A wider range of plant materials and tree species that are used as organic soil amendments in the subhumid tropical highlands should be included in future studies to enhance the mathematical predictability of their decomposition rates across differing environments in the tropical highlands.

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BIOGRAPHICAL SKETCH

Daniel Njiru Mugendi was born on June 8, 1961, in Meru (Tharaka-Nithi) District in Kenya. Mugendi attended Kirege Primary School between 1969 and 1975. His secondary and high school education were obtained between 1976 and 1981 at Ikuu and Nkubu High Schools respectively. Mugendi attended the University of Nairobi in 1983 to undertake a BSc in Forestry. In 1984 the Department of Forestry was transferred from Nairobi to Eldoret to start Moi University. In 1986, Mugendi graduated from Moi University with a BSc degree (honors) and was immediately employed by Kenya Forestry Research Institute (KEFRI) as a Research Scientist. He was posted to Machakos to work in Dryland agroforestry Research Project. Mugendi earned a MSc degree at the University of Nairobi between 1988 and 1990. In 1991, he was transferred from Machakos to Embu to work in the National Agroforestry Research Project. Mugendi is currently on study leave at the University of Florida where he is pursuing a doctoral degree specializing in agroforestry. Mugendi is married to Beatrice and they have two children, Lydia and Caleb.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

P.K.R. Nair, Chairman
Professor of Forest
Resources and Conservation

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Henry L. Gholz
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This dissertation was submitted to the Graduate Faculty of the School of Forest Resources and Conservation in the College of Agriculture and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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